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THE JOURNAL
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THE HELICOPTER ASSOCIATION
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BULLETINS OF

THE HELICOPTER ASSOCIATION

OF GREAT BRITAIN

1946-7

FIRST LECTURE 1946, *by*

RAOUL HAFNER *on*

DEVELOPMENT IN ROTATING WING AIRCRAFT

26th April, 1946, at Manson House, 26, Portland Place, London, W.1.

FIRST LECTURE 1947, *by*

Group Captain R. N. LIPTROT, C.B.E., on

A HISTORICAL REVIEW OF HELICOPTER DEVELOPMENT

12th October, 1946, at Manson House, 26, Portland Place, London, W.1.

SECOND LECTURE 1947, *by*

C. G. PULLIN, F.R.Ae.S., M.I.Mech.E

HELICOPTER RESEARCH AND DEVELOPMENT

9th November, 1946, at Manson Hous
26, Portland Place, London, W.1.

VELOPMENTS IN ROTATING WING AIRCRAFT

by RAOUL HAFNER

aoul Hafner came to this country in 1932 and continued his earlier ter experiments with the successful design and construction in 1937 of afner AR. III Gyroplane. He is now Chief Designer of the Helicopter tment of the Bristol Aeroplane Company.

his paper was read in the first instance on 6th March, 1945 before The l Branch of The Royal Aeronautical Society, and subsequently to a joint g of The Society of Licenced Aircraft Engineers and The Helicopter ation on the 27th April, 1946.

luction

the first instance, I should like nk the President and the com- members of the Bristol branch : Royal Aeronautical Society for vitation which they have extend- me to speak here on rotating aircraft.

ondly, I take this opportunity of ing Captain Liptrot, of the ., for a film on helicopters he kindly lent, and which will own later in the evening, and e Bristol Aeroplane Co. for cer- lata and information which they made available for this lecture.

garding the subject of the lecture, t confess I am faced with con- ble difficulties. Great advances been made in the last few years : rotating wing field, and today t embraces practically all branches ence.

elieve I am not making an over ent when I say that the rotary today is a much bigger and more licated subject than the fixed There is hardly one aspect of xed wing, which does not equally perhaps in a slightly modified apply to the rotating wing. But e other hand, there exist now a thousand and one headaches of the rotating wing variety, which the designer of fixed wing aircraft is very fortunate to miss altogether.

In deciding on tonight's subject, I had therefore the choice between a detailed analysis of a specific aspect of the rotating wing development, and a more general talk which, however, necessarily can only touch the fringe of the numerous problems.

I have been advised that the second course, that is a more general and popular discussion, would be the more appropriate one, as the majority of the audience is not likely to be sufficiently closely connected with this development to be interested in intricate technical details.

General Principles of Rotating Wing Flight

There are several forms of rotating wings which permit aerodynamic flight, but in tonight's discussion I have in mind only wings rotating in free air about a substantially vertical axis, and producing a force along this axis which is directly utilised to overcome gravitational and inertia forces. One or more such wings rotating about a common axis form a rotor, and the surface swept by the wings is

¶ *For printing purposes the Greek symbols within the text are reproduced in italics.*

known as the rotor disc. Let us at first consider the simple case of flight along the axis of rotation, or vertical ascent. This is the case of the propeller. We have a number of blades of suitable aerodynamic shape moving through air, due to their rotation about their common axis and their linear velocity along this axis. Propeller blades produce a steady lift which is a function of:—

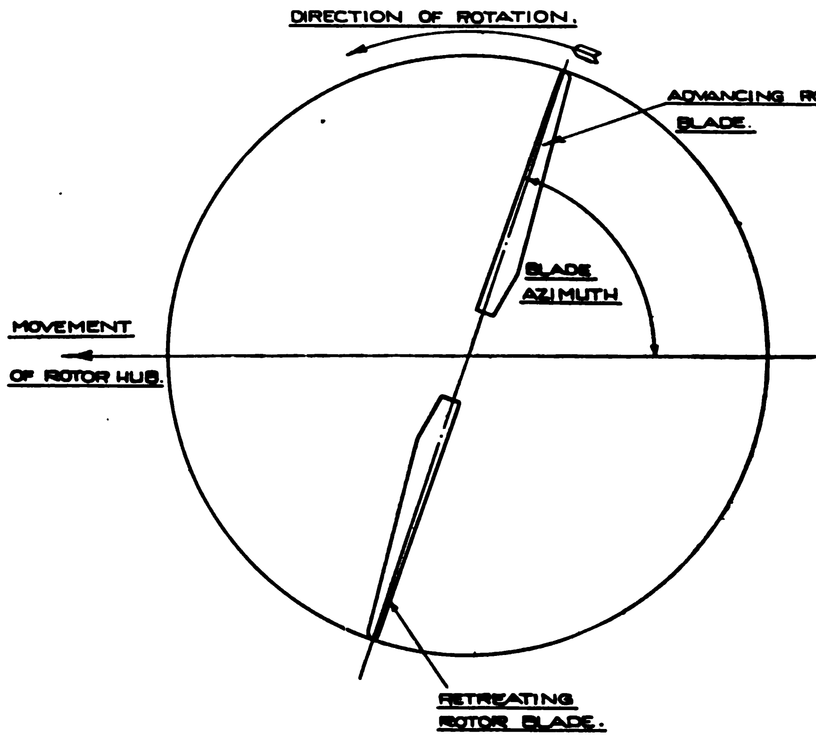
(1) The size and shape of the blades.
(2) Their incidence relative to the rotor disc.
(3) Their rotational velocity.
(4) Their axial velocity.

The lift, and this is important, does not depend on the *position* of the blade in the plane of rotation, or on the blade Azimuth.

The picture, however, changes if an additional velocity component is introduced, that is one in the plane of rotation.

To illustrate this, let us consider a rotor without axial velocity, but with a velocity component in the plane of rotation (Slide 1.)

In this form of flight, the Azimuth position of the blade is an important factor governing blade lift. It is easily seen that, on one side of the



SLIDE No 1.

rotor disc, where the blade may be said to be advancing relative to the rotor hub, the resultant velocity of the blade will be greater than that on the side of the disc where it is retreating. Thus we have here a cyclic change of speed. Unless, therefore, special arrangements are being made, this variable speed would result in a concentration of lift on the advancing side of the rotor, and consequently an undesirable rolling moment.

Quite apart from this there would be severe vibrations due to the cyclic lift change in the blades, which could not be tolerated.

A number of schemes have been proposed to overcome this difficulty. In the first instance, it would appear that the cyclic change of resultant blade velocity could be avoided, at the outset, by arranging for a cyclic variation of the rotational velocity of the blade, so that when advancing the blade would have a smaller angular velocity than when retreating.

Such cyclic change of angular velocity would involve, however, angular accelerations, which can be shown to be excessively high, and the solution of the problem in this form seems, therefore, unlikely.

Other schemes assume constant angular blade velocity, and consequently a cyclic changing blade velocity in forward flight, but propose to compensate by means of a cyclic change of other blade parameters governing lift.

Alternatively one could think of a variable blade area, or a telescoping blade, which would be retracted on the advancing side and extended at the retreating side. The technical difficulties of such arrangements, however, can be easily visualised. They are obviously impractical.

The next possibility is the cyclic variation of blade incidence. This is termed "cyclic blade feathering", and is of great practical importance, having been adopted in most modern rotary wing aircraft.

Its main advantage lies in the fact that only a few degrees of incidence change are necessary to supply the required compensation. This is performed by oscillating the blade about its longitudinal axis, which is characterised by a comparatively small mass moment of inertia. Hence, compensation by means of blade feathering involves only small inertia forces.

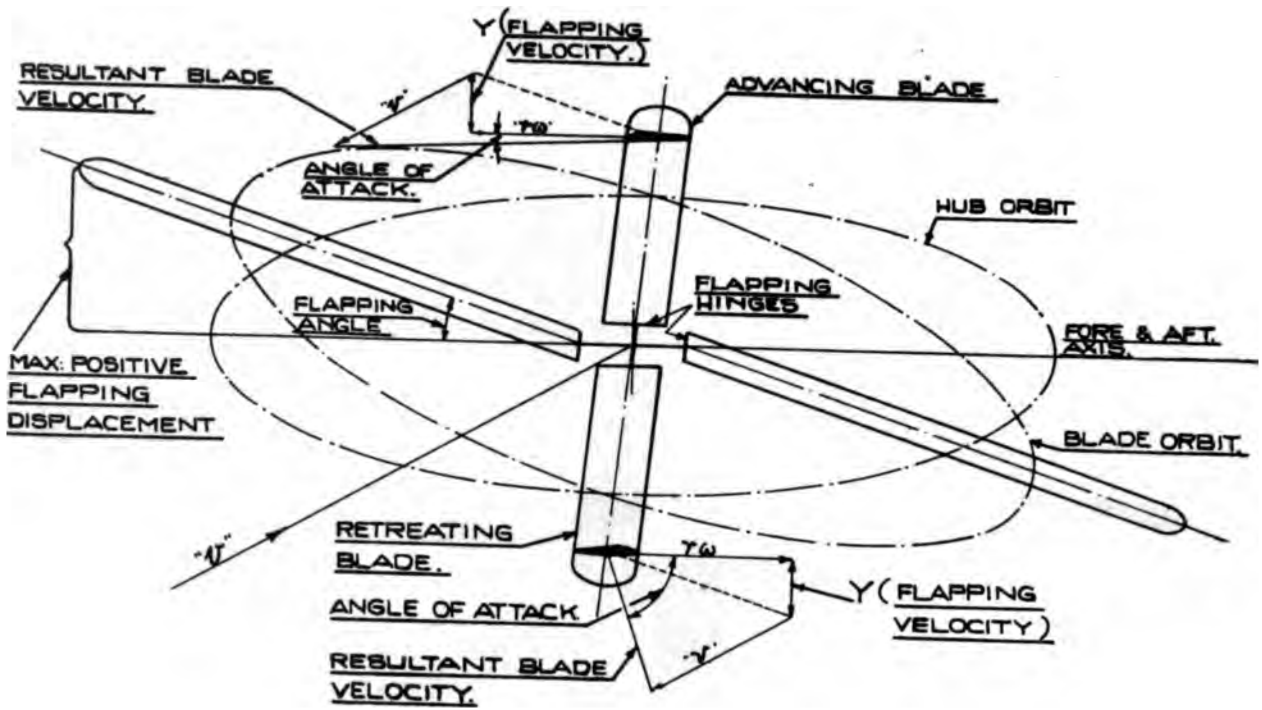
Another form of compensation is obtained through blade flapping. In this case the blade is articulated at the root, to enable it to oscillate, or flap, in a plane at right angles to the plane of rotation. The tip of the blade has therefore, apart from its rotational speed a cyclic velocity component at right angles to it. (Slide 2.)

From this diagram it will be seen that, whilst the blade incidence remains constant, the effective angle of attack is decreased when the blade has a positive or upward flapping velocity, and alternatively it is increased when the flapping velocity "y" is downwards. We see, therefore, that blade flapping in forward flight performs the same function as blade feathering. Both are, in fact, identical in aero dynamic respects.

To sum up, the feathering blade reaches a minimum incidence at the advancing side, and a maximum at the retreating side. At the fore and aft positions the incidence is at an average value.

In order to achieve the same object, the flapping blade must have a maximum upward velocity at the advancing side, and a maximum downward velocity at the retreating side. At the fore and aft positions the flapping velocity is nil.

The maximum positive, or upward, flapping displacement, however, occurs forward of the rotor, and the maximum downward flapping displacement is aft of the rotor hub.


Y (FLAPPING
VELOCITY.)
RESULTANT BLADE
VELOCITY.
"V"
"rω"
ADVANCING BLADE
ANGLE OF
ATTACK.
HUB ORBIT
FLAPPING
HINGES
FLAPPING
ANGLE
FORE & AFT.
AXIS.
MAX: POSITIVE
FLAPPING
DISPLACEMENT
BLADE ORBIT.
RETREATING
BLADE.
"V"
rω
Y (FLAPPING
VELOCITY)
ANGLE OF ATTACK.
RESULTANT BLADE
VELOCITY.
"V"

SLIDE No 2

I would like to add that this blade flapping in forward flight is quite an automatic movement—in no way controlled—so that articulated blades which are free to flap, automatically retain the equilibrium of lift in the rotor within a considerable speed range, and tend to suppress rotor vibrations.

Flapping blades have, however, another important property. During rotation the blade is subject to a considerable centripetal acceleration, causing a centrifugal inertia force.

In conventional designs this centrifugal force acting on the blade is approximately 12 times the blade lift.

The articulated blade will therefore assume a position of equilibrium where lift, centrifugal and centripetal forces are in balance.

This will be the case when the angle between the plane of rotation and the longitudinal axis of the blade, is approximately 1 in 12, or about 5°. This angle is termed the "coning angle" of the rotor, and the surface swept by articulated blades is therefore a very flat cone.

The important feature in this arrangement is the avoidance of bending moment at the blade root, and even at other points of the blade; the resultant bending moment is only of negligible proportions compared with that of a straight cantilever blade. This feature permits slender and, aerodynamically, very efficient blades, and has been the main reason for its almost universal adaptation in contemporary rotating wing design.

Indeed, this method of reducing bending moments due to blade lift has been extended to blade drag, which is intimately connected with lift, and we find today, in rotary wing practice, fully articulated blades which are not only free to flap, but are also free, to a certain extent, to oscillate individually in the plane of rotation.

These oscillations are termed "drag oscillations", and the operative hinges are called "drag hinges".

The Aero-Dynamics of the Rotor

The aero-dynamics of the rotor are considerably more complicated than those of the fixed wing, for the following reasons:—

In the study of the air forces on the fixed wing, it has been found expedient to regard the wing as stationary, and to observe the pattern of the airflow and the forces around it. The essence of this procedure is, that we are dealing with a static problem, and are concerned only with the components of space and force. There is not involved—and this is important—a variation in respect of time.

The theory of the potential flow, as well as the wing theory concerned with the lift over a finite span, are based entirely on this conception. The picture developed in these theories represents the static equilibrium of forces which is obtained once the wing has been in a certain attitude for a length of time, and there are no more changes with respect to time.

But for the rotor, such a conception is strictly not permissible. Consider in the first instance, the potential flow around the aerofoil.

The blades in their flight through air carry out a composite movement, consisting of rotation and translation. The resultant air speed, angle of attack and circulation around the aerofoil, change rapidly with time. In the modern rotor this cyclic variation has a frequency of the order of four to five cycles per second, so that the rate of change of magnitudes in respect of time is considerable.

A certain amount of investigation in this direction has been carried out in connection with flutter problems, in order to provide the necessary aero

dynamic derivatives for the dynamic equations, but there remains still a good deal to be done.

I would have liked to say more about this interesting subject, but unfortunately time doesn't permit, and so I confine myself to a few observations:—

We have today, for aerofoils, such data as the change of lift and drag with respect to speed, or with respect to incidence, or to Reynolds numbers, but for the rotor blade, in addition to this, the changes of air force in respect of $\dot{v}$ or $\dot{a}$ and $\ddot{a}$ are of importance, that is:—

$$\frac{\partial C_L}{\partial \dot{v}}, \quad \frac{\partial C_L}{\partial \dot{\alpha}}, \quad \frac{\partial C_L'}{\partial \ddot{\alpha}}, \quad \frac{\partial C_D}{\partial \dot{v}} \quad \text{etc.}$$

Until we know more about these derivatives we cannot, with confidence, attempt rotor calculations.

Let us consider next the air space close to the aero-foil, which is known as the boundary layer.

Skin friction comes from the shearing of air within this boundary layer, and is the result of the rate at which momentum is exhausted from this air. This layer is trailed behind the fixed wing as a turbulent wake, and once it has passed the wing—has no further effect on the aircraft.

This is not so in the rotor blade. Here the air, as soon as it loses momentum, becomes subject to centrifugal force, which moves it radially away from the centre of the rotor.

In addition to this, when the pitch setting of the rotor is close to zero, the wake of the blade is cut by the following blades, which amplifies the effect that I have just mentioned. This phenomenon can be studied in practice on any helicopter or autogiro rotor.

At zero pitch there is a very powerful radial flow in the plane of rotation of the rotor, consisting entirely of an from the boundary layer, which is fed by inflowing air from both sides of the rotor disc.

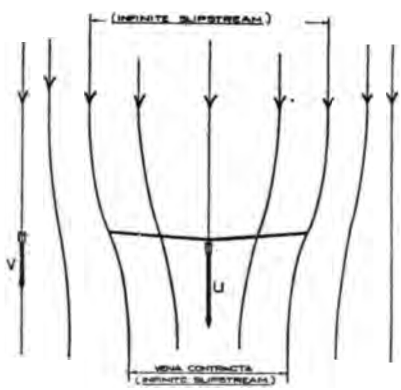
The work involved in this movement of air is very considerable, and all conditions of flight connected with pitch settings close to zero are, therefore, materially affected by this radial flow.

The next item on the list of specific rotor problems is the fact that rotary wing aircraft, slow though they are in the eyes of the pilot, fly really exceedingly fast. With this I mean that, in modern designs, the wing surface supporting the main weight of the aircraft moves at a rate of anything between 500 and 700 ft/sec.

This is a speed range where aero elasticity already plays an important part, and the design of the blade tip, from the point of view of flutter, as well as performance at these high speeds, requires special consideration.

To complete the list of rotary problems (which appear to be problems which have the habit of indefinitely turning up again and again) we come to consider the induced flow.

The calculation of the induced flow of a rotor in vertical ascent is relatively simple. It is similar to that of the pro-



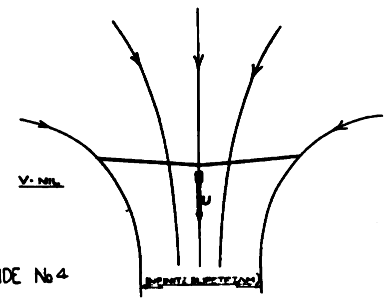
SLIDE No3

peller, which is well established, and the formulae which have been evolved for the propeller, equally apply to the rotor.

The induced flow for this flight case can be seen on the diagram. (Slide 3.)

The picture becomes, however, very different for other modes of flight.

The propeller Vortex theory breaks down already in the case of the hovering rotor. The strip theory, and the assumption of the induced velocity at the actuator disc being half of that in the vena contracta, is not valid any longer. The induced flow for the hovering helicopter is shown by this diagram. (Slide 4.)

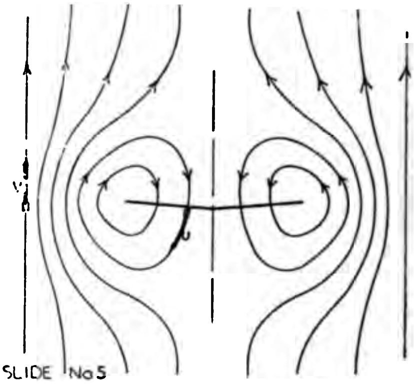


SLIDE No 4

Empirical extensions of the propeller Vortex theory, with limited validity, have been made, but we are still in need of a satisfactory theoretical investigation on this mode of flight.

The picture becomes still more complicated when we enter into the Vortex ring state. The rotor is in this condition of flight when the direction of the flow, passing through the actuator disc, is opposite to that of the outer air flow. The flow pattern for this case is shown in this slide. (Slide 5.)

We see here that the infinite slip stream has disappeared, and is replaced by a Vortex ring of air which completely envelops the rotor, and the outer laminar flow passes around this



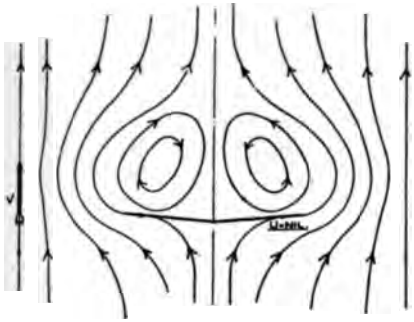
SLIDE No 5

Vortex ring, without coming in contact with the rotor itself.

There is, however, no clear demarkation between the outer air and that forming the Vortex ring. Considerable turbulence is in evidence, and there seems to be a continuous exchange of air between these two regions, resulting in a transfer of energy from the Vortex ring to the outer air. Such a transfer is, of course, essential for fundamental reasons, as otherwise the velocity of the finite mass of air within the Vortex ring, which continuously receives momentum from the rotor, would increase to infinity. The form of this energy transfer, and its behaviour, is therefore, a very interesting study, and requires to be analysed before a more exact calculation of the induced flow in the Vortex ring state can be attempted.

The Vortex ring state is bounded by two conditions. The first, which I have already mentioned, is the hovering condition. The other is the free wind-milling condition. In this condition the flow through the rotor disc is nil, or in other words, the rotor behaves like a solid disc.

There is a Vortex ring of smaller proportions immediately above the rotor. (Slide 6.)



SLIDE No6

Going a step further, we enter into the wind-mill-brake state. (Slide 7.)

In this condition the flow through the rotor disc is directed upwards, like that of the outer air flow. There is still a small Vortex ring situated above the rotor which, however, diminishes as the speed through the rotor disc increases.

The characteristic feature of the wind-mill-brake state, as distinct from the previous conditions of flight, is that energy is transmitted to the rotor from the air flow, passing through the disc. In other words, the rotor is receiving energy like a wind-mill.

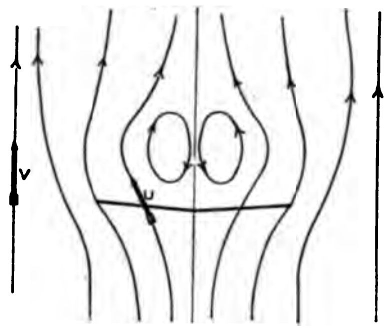
There is one particular point in the wind-mill-brake state which deserves special attention.

Every rotating rotor absorbes a certain amount of power, which is expended on the profile drag of the blades.

If, now, a point in the wind-mill-brake state of the rotor is found, where the work extracted from the air flow passing through the disc is exactly equal to the profile work expended on the blades, then the rotor is maintained in rotation without any power passing through the mechanical rotor drive. In other words, the rotor is free-wheeling, or is in auto-rotation. This feature is employed in aircraft known as rota planes or autogiros. The rotor of such aircraft is not power driven, but is auto-rotating in the manner which I have described. The rota-plane represents, therefore, one specific form of helicopter flight; one point, so to say, on the line extending from the power driven rotor to the power receiving wind-mill.

The helicopter can consequently descend with its rotor in auto rotation, and without the use of engine, provided appropriate adjustments have been made to the blade pitch.

We come now to the induced flow in forward flight.



SLIDE No7

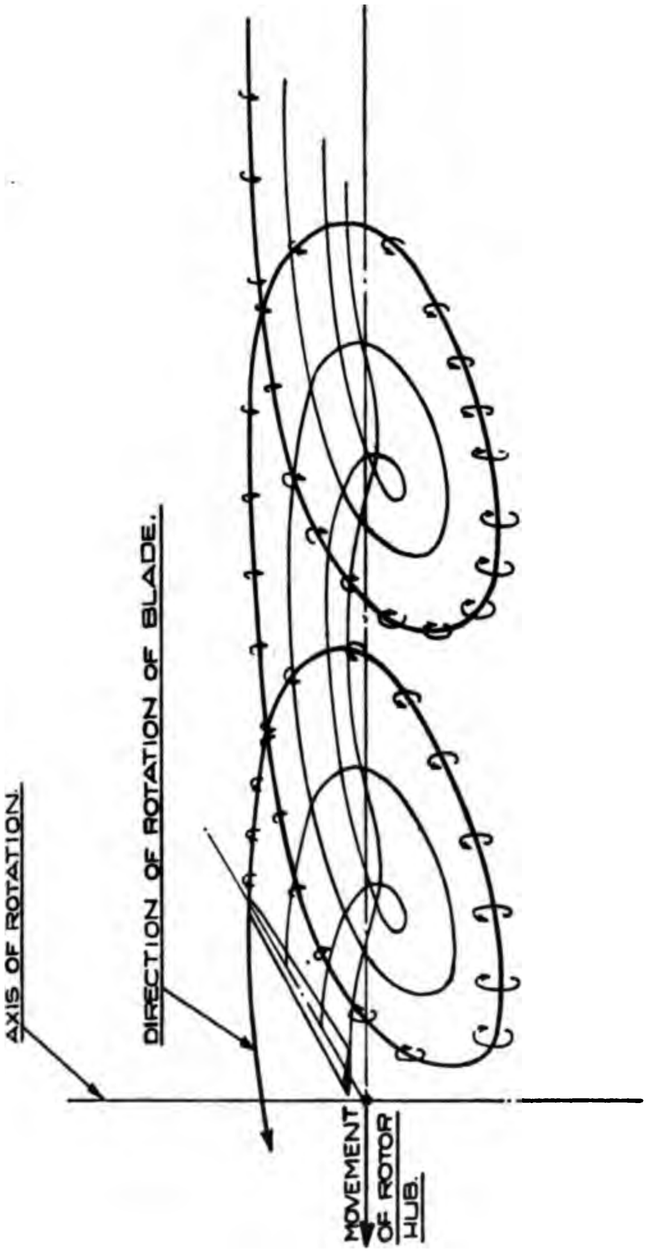
Lift of the rotor originates, of course, along the blade, exactly like along the span of a wing.

We know, however, that the movement of a blade is a composite one, and speed, direction and circulation, change continuously, with regard to place as well as time.

The Vortex sheet shed by such a blade is, therefore, necessarily of a complicated shape.

This diagram perhaps gives a rough picture of its geometry. (Slide 8.)

There is increased vorticity at certain points, due to the cyclic conditions to which the blade is subject, and these regions of increased vorticity are left behind in the path of the aircraft, similar, perhaps, to the Vortex pools from the oars of a moving rowing boat.


AXIS OF ROTATION.
DIRECTION OF ROTATION OF BLADE.
MOVEMENT OF ROTOR HUB.

SLIDE No 8.

There is usually more than one blade in a rotor, so that the Vortex sheet produced by a rotor is a pattern of N interwoven Vortex sheets, from N rotor blades.

It will be appreciated that a rigorous analysis of such a complex configuration is impossible, and far going simplifications must be applied to this picture in order to make it amenable to mathematical treatise.

Fortunately, there is a good deal of justification for simplifying the picture. The blades in a modern rotor rotate at a high rate compared with the forward speed.

This produces a tight pattern of coils formed by the Vortex sheets of the individual blades, which tends to level out the moving pattern in the Vortex sheet of the rotor.

Thus, the individual Vortices moving down stream merge more or less into a continuous Vortex sheet, which is trailed by the rotor as a whole, and which is acceptable to calculation. We make, therefore, the assumption, notwithstanding the fact that the lift originates from the rotor blades, that it is formed at the rotor disc as a whole, or simpler still, along the lateral rotor diameter or span of the rotor.

This assumption permits the calculation of the induced flow in the span wise direction by the orthodox manner known in fixed wing design. As regards the fore and aft distribution of induced flow, one assumes a slight curvature of airflow, which is confirmed by experience.

Having made allowance for the induced flow in this manner, the further calculations for the rotor blade itself are made on the assumption of two-dimensional-flow conditions.

Let us now make a brief investigation into the aero dynamics of the blade.

We have seen that a blade element in forward flight is subject to speed variation, which depends on the ratio between forward speed and the speed component due to rotation. Thus, it varies directly with forward speed, and indirectly with the rate of rotation, and the distance of the blade element from the rotor centre, i.e. the smaller the radius the larger the speed ratio.

We have seen that, in order to maintain a constant lift throughout rotation, this speed variation is compensated by a cyclic change of angle of attack. As there is a larger speed ratio near the root than near the tip of the blade, it might be desirable to arrange for a larger cyclic change of blade incidence near the root than near the tip. This clearly means cyclic twisting of the blade, which for obvious reasons cannot easily be done. As a compromise arrangement, a mean cyclic change of incidence, which is the same for all blade elements, is usually provided for by means of blade feathering or flapping. This meets exactly the requirements of the most important portion of the blade around three quarters radius from the root, and all the other blade elements, inwards and outwards of this region, receive only an approximate speed compensation.

In order to meet the conditions for various ratios between forward speed and rotational speed of the rotor, the mean cyclic change of incidence can be varied by increased or decreased blade feathering. Thus for instance, on a rotor moving at slow forward speed but at a high rotational speed, the blade feathering needed is very little, whereas, on the other hand, considerable feathering is required for a small and slow rotating rotor moving at high forward speed. From this it will be seen that, in a rotor in forward flight, the conditions in the rotor disc vary from point to point, i.e. with respect to radius as well as Azimuth, and analytical calculations for this reason tend to be rather cumbersome. However, in order to obtain a convenient datum for performance calculations,

which do not involve analytical treatment, but are based on semi-empirical data, the definition "tip speed ratio" has been found expedient. This is the ratio between the forward speed and the velocity component due to rotation of the blade tip, or, in mathematical terms, the tip speed ratio is

$$\frac{V}{R\,w}$$

where V is the forward speed in the plane of rotation, R the blade radius, and w the angular velocity of the rotor.

I will show now that there are definite limits in the tip speed ratio of a rotor, beyond which satisfactory operation is not possible.

Let us assume a rotor with a blade tip speed of 600 ft/sec, and in the hovering condition, an average lift coefficient of .4.

Take now this same rotor at the forward speed of 225 ft/sec, or at a tip speed ratio of 225/600, or .375. For the working portion of the blade at ¾ radius the rotational speed component is ¾ of 600=450 ft/sec., so that the speed ratio in this region is of the order of 225/450 which is ½.

On the advancing side of the rotor, the resultant blade speed in the working region is therefore 1½ times its normal rotational speed, whereas on the retreating side it is only half of it. If no speed compensation was provided for, the lift on the advancing side would consequently be 3 half squared, or nine quarter times that of the lift when hovering. In order to compen sate for this, the lift coefficient on the advancing side is reduced to four ninths of the original value, i.e. it is reduced from .4 to .17, whereas on the retreating side the lift coefficient will be 4 times that of the original value, or 1.6.

A lift coefficient of 1.6 is a fairly high value for an aerofoil, which, in this condition, is probably near the stalling point.

This brief analysis has shown, therefore, that the tip speed ratio of .375 has brought the working portion of the blade on the retreating side close to stalling point. A further increase of tip speed ratio is obviously not possible, and we may regard, therefore, this figure as a limiting value. Any further increase of forward speed can, therefore, only be achieved by increasing the tip speed of the rotor proportionally, so that the tip speed ratio remains at the value of .375, but, in the present case, the resultant speed of the blade tip on the advancing side is already about 600+225 ft., equalling 825 ft/sec. This velocity at sea level represents a Mach number of .73. We are here, therefore, fairly close to a critical speed, in view of aero compressibility, so that we have, with 225 ft/sec. or 150 m.p.h., indeed come close to the maximum forward speed at which our helicopter can safely be flown. Exact investigations, allowing for finesse in design, show that, with today's knowledge, we could fly helicopters up to speeds of approximately 180 miles an hour. Beyond such speeds there would be either stalling on the retreating side, or alternatively, at the advancing blade tip, difficulties due to aero elasticity.

Control of Rotary Wing Aircraft

A few words now about control. The most general movement of a body in space is defined by its 6 degrees of freedom. 3 degrees of translational freedom of movement and 3 degrees of angular freedom of movement. Such a body can turn about all possible axes, and, quite independently from this movement, can trace any path in space. If such a body were controlled, its control would comprise at least six independent control components. However, controlled flight is possible with less degrees of freedom, and therefore, not all of the 6 control components are

necessary. As we require a minimum of one control for one dimensional movement, and 2 control components for two dimensional movement, so, by analogy, we require a minimum of three dimensional control components for movement in space. In the conventional aeroplane there are the throttle control, pitching control, and, as the third control, either the Yawing or the rolling control. The throttle or power control provides for linear acceleration along the longitudinal axis of the aircraft. The two other controls determine angular accelerations of the aircraft. There remain, consequently, three degrees of freedom of movement, which are not independent, but which, in one form or another, are coupled with the directly controlled movements. Thus, the aeroplane cannot, for instance, perform a rotation in pitch or roll, without these angular movements affecting the flight path, or, in short; into whatever direction the aeroplane turns, there it has to go.

I have spoken of either the rudder or aileron control as a minimum requirement for controlled flight.

Conventional aircraft, however, possess rudder *and* aileron control, and have thus four independent controls, and four degrees of freedom of movement.

There is, therefore, one redundant control above the absolute minimum which enables the aircraft to carry out assymetric flight manoeuvres.

If rotating wing aircraft were required only to possess the limited degree of freedom of the aeroplane, the same controls would suffice. But the outstanding manoeuvrability of the helicopter is due to an additional degree of freedom of movement, making five in all.

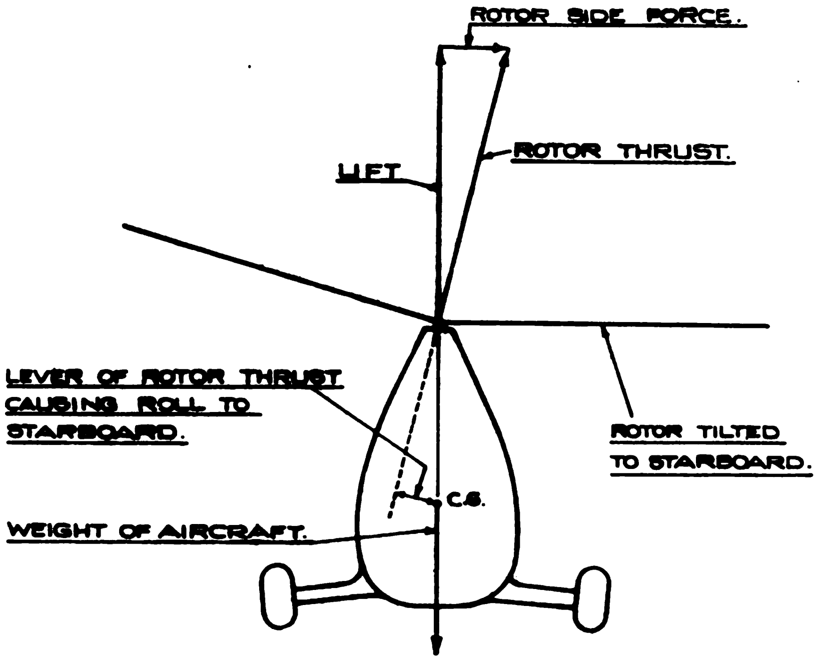
The helicopter distinguishes itself from the fixed wing aircraft by the fact that it is not forced to fly in the direction where its nose points. We have seen that the aeroplane, which possesses rudder and aileron control, can already divorce rotational from translational movement.

The helicopter in slow flight can move in any direction in space, without noticeable change of attitude relative to the ground.

The additional freedom of movement of the helicopter would not be possible without a further independent control component. This additional control component is the height control, and determines the linear accelerations in the vertical axis of the aircraft. The remaining controls of the helicopter are analogous to the respective controls in the aeroplane, but they are not quite identical in operation. The control components served by the control column are, in the helicopter, termed the Azimuth control. In the low speed range they determine linear accelerations in lateral and fore and aft direction. Therefore pulling the control column back does not result in a climb, as one would think, nor pushing it forward in a loss of height, but merely in a change of speed in the horizontal plane. Only when higher speeds are attained does the control column effect movements in the vertical direction, like in the aeroplane.

As I have already mentioned, rotary wing aircraft are required to operate at a speed range commencing at zero speed. It is, therefore, obvious that the conventional type of control in the fixed wing aircraft, that is by means of adjustable control surfaces, is unsatisfactory, as it would become inoperative at zero flying speed.

A variation of this principle is obtained by utilising the induced air flow which is always present where a load is carried aero-dynamically. Although all possibilities of this nature are by no means exhausted, the general impression from the various attempts made is that the available air flow is not powerful enough to give effective control. The control surfaces would



SLIDE No 9

be rather large, and the control cumbersome, so that apart, perhaps, from the control in yawing, the deflection of the slip stream of the rotor is unlikely to be used for the purpose of controlling the aircraft.

A more important argument, however, for not controlling roll and pitch in this way, is that this can be done, very much easier and more effectively, by the rotor itself.

The rotor produces an aero-dynamic force carrying the entire weight of the aircraft, and this force lies along the axis of rotation. By moving the axis of rotation, and with it the rotor thrust relative to the aircraft, a very powerful control can be obtained, which is independent of any translational speed of the aircraft. The most elementary form of control, in this way, would be the shifting of the rotor bodily in its plane of rotation. (Slide 9.)

The second possibility, which is of great practical importance, is the angular displacement of the rotor relative to the aircraft. If the rotor is tilted to starboard, the aircraft will at first accelerate in this direction and, as the rotor is usually placed above the C.G. of the aircraft, eventually roll to starboard, and similarly, if the rotor is tilted backwards, the aircraft will accelerate backwards, and eventually pitch in the positive sense.

There are various methods of tilting a rotor. The most simple form comprises a rigid rotor like a propeller, which is spherically hinged about its centre of rotation, and is connected to a suitable control gear, in order to permit inclinations in all directions. This form represents a direct control, and consequently the work to overcome inertia and gyroscopic forces must be provided by the pilot, or another external source of power. Such a control is necessarily very heavy in operation.

and larger rotors would be quite unmanageable by this method.

Another method of control is by means of cyclic pitch variation. In this form a cantilever rotor blade is rotated about the longitudinal axis, like the blade in a variable pitch propeller, but the pitch change is of a cyclic nature, so that there is more incidence, and consequently more lift, on one side of the rotor than on the opposite. In this way the air is made to do the work of tilting the rotor. The serious drawback to this scheme, however, is the gyroscopic couple due to the rate of change of rotation of the rotor, which is not catered for in the control, and which is making itself felt as a disturbing element during control movements.

The third, *and most important,* method of control, is that of the articulated rotor. Two forms can be distinguished which are aero-dynamically identical. There is, in the first instance, the direct hub control which we find in the autogiro. We have here a set of flapping blades which are articulated to a central hub. This hub, in turn, is pivoted at the top of the pylon, and connected with a control gear enabling it to be tilted in any Azimuth direction.

Let us assume a hub and rotor rotating in the same plane. Tilting of the hub, i.e. angular displacement of it relative to the momentary plane of rotation of the rotor, causes, in the first place, a cyclic pitch change in the blades, which produces an aero-dynamic couple on the rotor. This couple performs the change of rotation of the rotor which as before induces a gyroscopic couple. Owing to the articulation of the blades however, the gyroscopic couple cannot be transmitted to the hub and control, but is balanced by air forces set up by the flapping of the blades. The control is therefore free from all severe rotor forces, and the only indication by which these forces are experienced is a time lag in the control. In this way, any angular movement of the hub, after a brief time lag, is followed up by the rotor disc, which always tends to align itself with the plane of rotation of the hub.

The second form of control for the articulated rotor was demonstrated in the Hafner gyroplane, and is used in most helicopters.

The rotor blades which, apart from flapping can be feathered about a longitudinal axis, are linked suitably to a spider or swash plate, or the like, which in turn is connected to the pilot's controls, and can be tilted in any Azimuth direction. The tilting of the control spider, like the tilting of the hub in the autogiro, causes, in the first place, a cyclic pitch change in the rotor, which produces an aero-dynamic couple, including the rotor disc, and all further reactions are exactly as in the tilting hub control.

Thus, the spider performs the function of the tilting hub, and the rotor orbit will always tend to align itself with the plane of rotation of the control spider or the control orbit, and any movement of it, subject to a very brief time lag, is copied by the rotor.

To sum up, the rotor control means essentially tilting of the rotor thrust. This produces horizontal aero-dynamic force components, which accelerate the aircraft in this direction. Further, owing to the fact that the rotor is above the C.G. of the aircraft, this side force, acting at the rotor head, induces a rotation of the aircraft.

Types of Rotary Wing Aircraft

I have pointed out that the autorotating rotor, which we find in the rotor plane, does not absorb power, but performs merely the function of a wing. This type of aircraft is, therefore, very similar in principle to the aeroplane, and flies in the same manner.

Rotor planes are usually fitted with an auxiliary drive for the rotor, which permits initial acceleration of the rotor prior to take off. In certain designs the speeding up of the rotor on the ground is carried beyond normal flying rotor speed, in order to utilise kinetic energy stored in the rotor, and obtain a direct or jumping take off.

Many versions of this type of aircraft have been constructed, but since the renaissance of the helicopter, the auto giro has lost most of its selling points.

Today the helicopter is in the centre of the rotary wing development. There are many forms of helicopters. Let us first consider the single rotor helicopter.

Its characteristic feature is the compensation of the aero-dynamic rotor torque, which is done in various ways. There is the jet driven rotor, which carries power jets at the tip of the blades, and the fuselage is consequently free from torque. The high velocity of the blade tip is particularly suitable to give high jet efficiency.

The most simple arrangement would be one where the whole power unit is confined to the blade tip, with only fuel pipes and controls leading to the rotor centre. There are, however, a number of serious problems connected with this arrangement, and its solution must be left to the future.

The second possibility is the combination of blade tip jets, with a central power unit supplying compressed air, which is fed through the hollow blade to the tip.

This arrangement suffers from frictional losses at the walls of the tunnel, which contains at least two 90 degree turns.

Another arrangement comprises a conventionally driven rotor and a jet, arranged at the tail of the fuselage, so that its thrust produces a moment about the axis of rotation of the rotor. This is not strictly a power jet, but a static thrust producing device. As such its efficiency is not very high, because, the jet cross sectional area being relatively small, the static thrust can only be obtained at the expense of high jet velocities and, consequently, power.

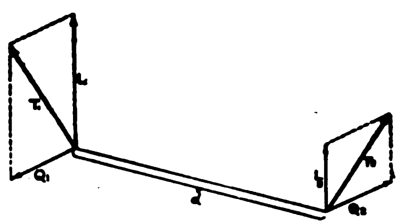
Another form of torque compensation utilises the induced flow of the rotor. Suitably shaped vanes are placed in this flow which produce the required compensating torque. This scheme has a valuable feature, in that it recovers the rotational momentum and energy, which otherwise is lost in the slip stream.

Considering now the twin rotor helicopter, we have first the type where the rotors rotate about parallel axes, but in opposite directions. It can be shown that two counter rotating rotors are most efficient if they are identical in geometry. That is, equal in size, tip speed, lift etc. They can be arranged, side by side, or behind one another.

Alternatively, the rotor discs can over-lap, partially in the case of intermeshing rotors, or fully when they are co-axially one above the other. Any over-lapping of rotor area, means, however, a reduction in supporting surface which results in increased induced losses. On the other hand, non overlapping rotors necessitate always relatively heavy supporting structures.

An example for a side by side rotor helicopter is the Focke Wulf, whereas the Breguet helicopter represents the co-axial type.

So far we have considered parallel axes of rotation.



$Q_1 - Q_2$

SLIDE No 10

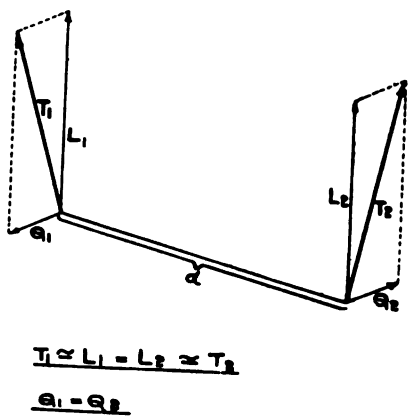
Now we come to twin rotors, the axes of which are inclined to one another, and do not intersect. The torque compensation of such rotors is based on very different principles. In the first instance, the torques of such rotors, do not add to zero, but leave a resultant torque, which is compensated in the following manner. (Slide 10.)

The thrusts T1 and T2, of the rotors which lie along the respective axes of rotation, can be resolved in two-components, L1 and Q1 and L2 and Q2.

L1 and L2 represent together the total lift of the helicopter, whereas Q1 and Q2 form a couple with the lever *d*, which is the distance between the two rotor axes, and this couple is adjusted to provide the torque compensation for these two rotors.

It is obvious that the components Q1 Q2, which don't contribute towards lift, should be as small as possible, and this can be done by making *d* large.

There are a number of configurations on this principle.



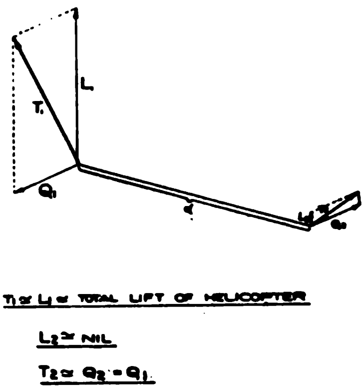
SLIDE No 11

Consider two rotors of equal thrusts. *d* being large, and consequently Q being relatively small, we can see from this diagram that the angle between the axes of the two rotors is quite small, and both lie in the general direction of lift. (Slide 11.)

The Florine helicoper is an example of this arraugement.

Now let us consider 2 rotors of different size. (Slide 12.)

In this case the large rotor with the large thrust determines the general direction of lift, as we can see in the diagram, whereas the small rotor is mostly concerned with producing the force Q2.



SLIDE No 12

The well known Sikorsky helicopter is an example of this type.

One could make a long list of possible helicopter lay outs, and what the future helicopter will look like we frankly do not know today. There are so many factors which will be thrown into the scales in the coming years, that it would be futile today, to attempt a prophecy on this development.

There are, however, a few indications based on general principles and natural laws, which permit a limited statement. In my opinion, the small helicopter which carries the equivalent

of a car load, will be of the single rotor type, or at least, have only one rotor to supply the main lift. In the larger helicopter, which carries something like a bus load, the lift will be equally shared between 2 rotors.

The Helicopter as a means of Transportation

After this short description of the rotary wing aircraft and its most important representative, the helicopter, I should like to say a few words on its possible uses in the future.

I have made reference already to the size of helicopters.

I would add that it can hover and manoeuvre exceedingly well in confined spaces, and, on the other hand, can travel at speeds up to 180 miles per hour. Regarding cruising speed for the near future, a figure of perhaps 100 m.p.h. is near a practical mark.

The helicopter can operate at day and night, and can fly in very adverse weather conditions. We know that, in the case of an engine failure, controlled flight can be maintained, and a safe landing can be performed. For such an emergency landing, an area of 100 yards in diameter is ample, the actual landing run being of a length of 10 to 20 yards only.

There will, of course, be many specific uses for the helicopter, for instance, as weight lifting gear in ports and mines, and in Civil Engineering works, where cranes are not practicable; also for police and military uses.

A seemingly unlimited range of proposals of this sort have already been made, and it is not my intention to add here to this list.

What I have in mind, however, is the helicopter as a means of transportation in competition with already existing forms of transport.

Let us consider a probable ground organisation for such helicopter service.

This sketch shows a typical helicopter landing and-parking place, as I visualise it. The landing pitch itself is a circular area of 100 yards in diameter. There is no reason why such a place should not be situated in a built up area, providing there are no high obstacles in the vicinity, preventing an approach along a flying path of 30 degrees slope. (Slide 13).

This provision is necessary to enable emergency landings. Normal take off and landing are made in such a manner that, at any instance during the manoeuvre—should an engine failure occur—the pilot is in a position to force land on this landing pitch. For this reason take off and landings are made facing into wind, and the flight path during take off is in the direction upwards and backwards.

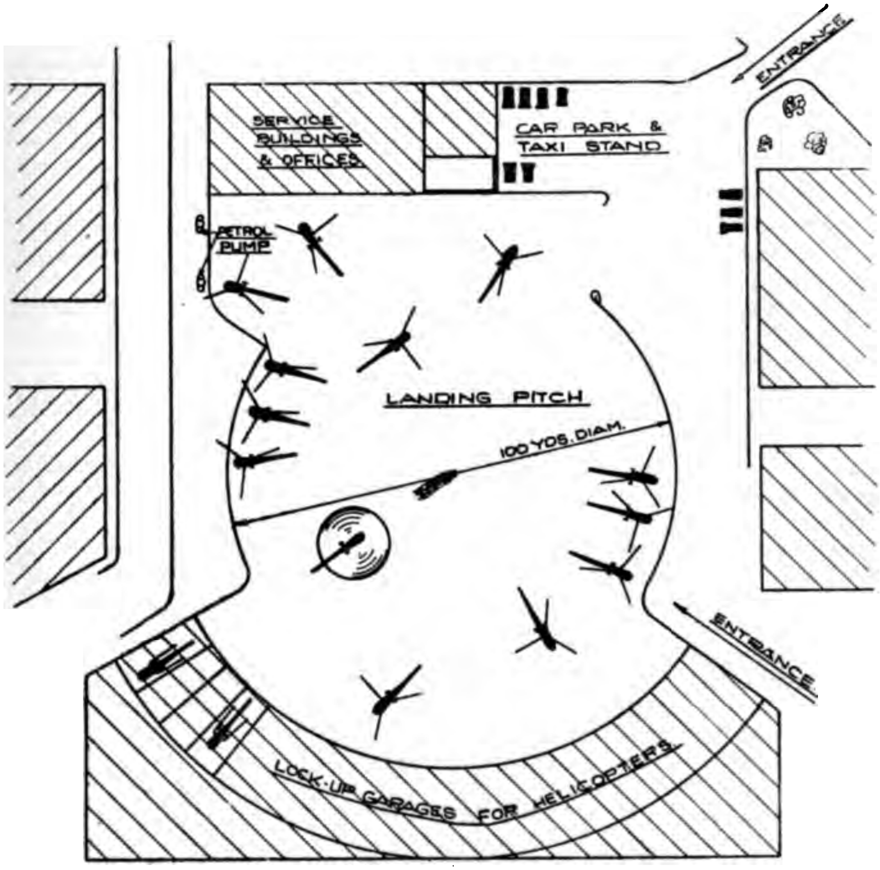
A diametrical strip of the landing pitch in the direction of wind is always kept free for take off and landing, and the remainder of the area is used as a parking place for helicopters. Adjoining the pitch we have lock up garages for helicopters, petrol pumps and service buildings, and the necessary office accommodation, with telephone facilities etc.

Preferably, such a helicopter station should be combined with a car service station, and a taxi stand and car park should be included.

There is nothing elaborate about this lay out, and the initial expense and maintenance costs should be very moderate.

I visualise these helicopter stations distributed densely over the countryside, as well as in towns. They are really only a glorified road-side car service station, and I feel, therefore, that once the helicopter is available, and subject to suitable guidance from the appropriate authorities, private enterprise will see to it that they grow like mushrooms.

I am afraid I had not time to discuss the efficiency of the helicopter, and therefore have no basis for its running costs.



SLIDE No 13

From investigations which have been made on these lines, we know today that it is possible to build helicopters which will be able to operate at a cost of approximately one and a half times that of taxis. This estimate is subject to a fair taxation policy, that is low taxes on aviation fuel, and no direct taxation on the helicopter, at least in the early stages of its development.

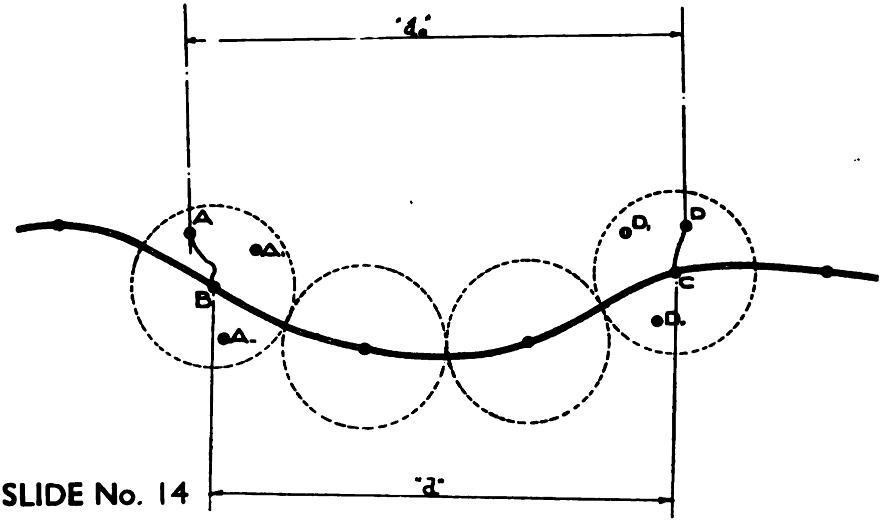
Assuming now a helicopter service based on these lines; what would be its chances in competition with other means of transport?

It is necessary here to establish a few definitions which apply to any form of transportation or travel.

A journey has a starting point A, and a point of destination D. (Slide 14)

The distance of transporting *do* is the length of the straight line connecting A and D.

The major part of the journey is performed by the selected form of transport i.e. by air, road, rail etc. It commences at B, the nearest practical point to A for embarkation, and terminates at C, the nearest practical point to D for disembarkation. The distance between these points, the straight line BC, is defined as *d*.



SLIDE No. 14

This leaves short distances AB and CD at the ends of the journey. Their length varies, of course, with the circumstances, and depends mostly on the form of service employed over BC. They may be nil in the case of a direct "door to door" service. Alternatively they are covered by another, usually inferior, form of service to that selected for the main distance BC.

The difference between AD and BC is:—

$$\Delta d = d_0 - d$$

Δd may be positive or negative, as can be seen by moving the points A and D, and is usally small compared with the total distance. For a large number of journeys Δd averages zero, which will be appreciated if a large number of points, A_1, A_2, A_3 etc., are assumed in the neighbourhood of B, and a similar number of points D_1, D_2 D_3 around C. The mean journey distance for all combinations of A and D is clearly equal to BC, which means

$$\Delta d \longrightarrow \text{nil}$$

The time needed to travel from A to D is t_0, and the time for the journey from B to C is t, the difference is defined as

$$\Delta t = t_0 - t$$

Now Δt varies with circumstances, depending on the length of the subsidiary journeys AB and CD, on the time for embarkation and disembarkation, and other factors.

It is clear, however, that for a large number of journeys, the average Δ does not approach zero, but has a definite value. This value can be shown to be a constant for a given form of service, and is practically independent of the length *d* of journey. It is therefore, suitably termed the "marginal time loss".

Now the rate of progress along BC, or the mean cruising speed along this line is defined as:—

$$V_m = \frac{d}{t}$$

In a similar manner the mean effective speed of the whole journey from A to D is

$$V_e = \frac{d_0}{t} = \frac{d + \Delta d}{t + \Delta t_0}$$

however, because Δd averages zero.

We can write

$$V_c = \frac{d}{t + \Delta t}$$

which, with substitutions, gives the following expression

$$V_e = \frac{V_m}{1 + \Delta t\,(V_m/d)}$$

We see, therefore, that the mean effective speed depends on the mean cruising speed, the length of the journey, and the marginal time loss.

The mean cruising speed, in turn, depends on a number of factors.

(1) The maximum cruising speed obtainable with the type of transport employed.

(2) The ratio between the lengths of the straight line BC and that of the actual path of travel.

(3) The number of intermediate stops, or points, which for reasons of safety or otherwise, must be passed at a speed which is less than the maximum cruising speed.

(4) Weather conditions, etc.

The marginal time loss depends mostly on the density of the points of embarkation or disembarkation, which determines the length of the subsidiary journeys. Further, the speed of transportation on subsidiary journeys, the time lost in changing vehicles at B and C, and finally, the average time table loss, which is the average time needed to wait for connections.

On this basis let us now consider air transport by air liner.

I assume, in a future service, an economical cruising speed of the order of 300 miles per hour.

In a country like England, there will be air ports at average distances of 65 miles. They cannot, of course, owing to their size and the nature of the air service, be in towns or centres of activity, which results in an average of 39 miles, for both subsidiary journeys to and from the air port.

These figures substituted in the formula for mean effective speed give now the very interesting curve A. (Slide 15.) The remarkable fact arising from this curve, is a pronounced decrease of mean effective speed of transportation with the length *d* of the journey.

We see here, that even under conditions of an efficient air service, which, it is hoped, will be attained at some future date, the mean effective speed of a journey of, for instance, 100 miles, would only be of the order of 30 miles per hour. It is obvious, therefore, that the air liner, is quite unsuited for short journeys.

Let us now see how rail transport compares. The Railway Companies have lately issued a statement, which, amongst other points of information, hinted at possible future speeds on railways.

I have taken some of their figures.

Usually, for short distances below 60 miles, the journey is made by a local train, and for distances of more than 60 miles, by express trains, with the use of local trains at the end of the journey.

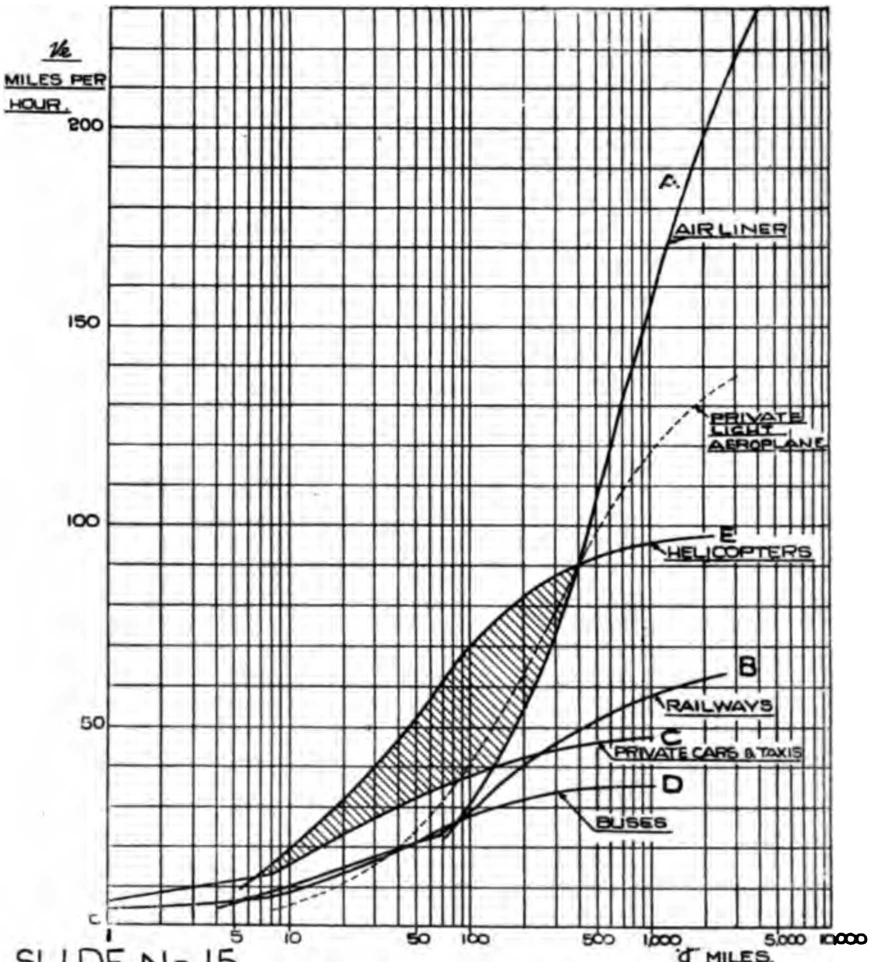
I have assumed a mean cruising speed for express trains of 65 miles an hour.

To attain this the train would have to run at a speed of over 80 miles per hour, for a good deal of the journey.

Owing to the great density of railway stations, and the fact that they are suitably placed with regard to centres of activity, the average marginal time loss for rail travel is better than for air travel.

It works out at approximately 40 minutes.

These figures give the curve B for the mean effective speed of rail transport.



SLIDE No 15

As regards motor road transport, we face the following facts :—

The private car and the taxi represent a "door to door" service. There is, therefore, no marginal time loss in this case.

As regards bus services, and under this category I would put the special railway services which are provided in densely built up areas, such as the underground and suburban lines, there is only a very small marginal time loss, of the order of 20 minutes.

On the other hand, however, the mean cruising speeds for these forms of transportation are low, due to the frequent stops or delays, which are necessary in the interests of safety.

As regards road transport, I have read with interest the proposals for roads and highways, which have been forwarded by the Post War reconstruction Committee, of the British Road Federation, and which indicate a scheme of motor highways for fast motor road travel, and a number of schemes for road traffic in built up areas.

On this basis I have assumed, as a mean cruising speed for cars, 45 m.p.h. on motor highways, which includes occasional stops, and a mean cruising speed, in built up areas, of 16 m.p.h.

The corresponding cruising speeds for buses are assumed to be slightly less.

Substituting, now, these figures in our formula for a mean effective speed of transportation, we obtain two curves C and D.

As regards air travel by helicopter, I have assumed a taxi service.

This means essentially, that aircraft do not fly to time tables, but meet exactly the wishes of the traveller. This would apply, of course, equally to the private owner's helicopter.

I have assumed twice as many helicopter stations as railway stations, excluding those of Urban and Suburban lines.

Thus, for instance, Bristol and district would have 15 to 20 helicopter stations, and a smaller town, like Weston-s-Mare, 2 or 3.

On this basis, the average marginal time loss works out to approximately 20 minutes.

The cruising speed of the helicopter is of the order of 100 miles per hour.

The mean effective speed of helicopter travel, on this basis, is given by curve E.

We are faced now with a very interesting comparison between the various forms of transportation.

The curves intersect each other, and it can be seen that the private car, or the taxi, is clearly the fastest form of transportation for short journeys, whereas on the other side of the scale, the air liner is unchallenged.

I have excluded from this comparison the private owner's aeroplane, because it cannot fly at night—at least I would not—and it is too much dependent on weather conditions.

However, a representative curve for mean effective speed is shown dotted in the diagram.

If we observe the curve for the helicopter, we find that it is faster than any other form of transport for journeys between 10 and 400 miles. In particular, if we consider journeys of the order of 120 miles, we find that it is nearly twice as fast as any of its competitors.

To sum up.

I believe the helicopter will be more expensive to run that the car or the taxi, but it will be by far the quickest means of communication for typical journeys in this country. For instance, from here to London, or from London to Birmingham, or from everywhere in England to Newmarket, or the sea-side.

There is no need for me to stress the fact that all the figures which I have quoted, have been, of course, to use the popular phrase, "cooked" to a considerable extent, and the conclusions at which I have arrived are highly optimistic.

Nevertheless, think of the possibilities! the chance to free yourself of cross-roads and roundabouts, of speed limits and stop lights, of time tables and waiting rooms! Think of the wing that flies in circles, but will give you the pleasure of travelling straight!

BULLETIN

MARCH

1947

HELICOPTER MEETING

in the

HOUSE of COMMONS

An informal meeting for the benefit of Members of Parliament was arranged by the Association on Wednesday the 29th January at the invitation of Sir Basil Neven Spence M.P. Three of his colleagues, Major Duncan McCallum, M.P., Major J. Macleod, M.P., and Mr. Malcolm MacMillan, M.P., also sponsored the meeting, which was instigated after a visit to Heston where they witnessed a brief demonstration of the possibilities of rotary wing flight.

The meeting was held in the Grand Committee Room, Westminster Hall, House of Commons, and the Association was represented by the following Council Members:—H. A. Marsh (Chairman), R. A. C. Brie, H. M. Yeatman and N. J. G. Hill. The Honorary Secretary also attended. The main interest in the discussion was centred around the possibilities of using the helicopter as a means of transportation in the Western Isles, Shetland and Orkney, although many questions of a more general nature were dealt with.

The film, "The Story of the Helicopter" was shown to the meeting and was viewed with great interest. This film, as the majority of members will no doubt recall, outlines briefly the background of the helicopter from Leonardo da Vinci, and, passing through some of the earlier helicopter attempts to the success of Juan de la Cierva with the Autogiro, it leads up to the experiments of Igor Sikorsky. The main body of the film deals with the flying characteristics of the Sikorsky types, the V.S.300, and the YR.4, taking the story up to about the beginning of the year 1944.

The Chairman explained to the meeting after the showing of the film that considerable further success had been achieved since that date, but that the film records depicting these recent developments were not yet available.

There followed a general discussion lasting about 30 minutes, during which time questions by various Members of Parliament covering such subjects as payload, engine failure, jet propulsion, bad weather flying and operation costs, were answered by Wing Commander Brie and the other Council Members present.

Finally, the meeting was closed with a motion of thanks from Major Duncan McCallum to the Association for the arrangements made and for the information which had been forthcoming.

He was assured by the Chairman, in reply, that the Association would be pleased to be of further assistance if so requested, in pursuance of its main object of furthering the development of rotating wing aircraft.

NEW MEMBERS

The following have been elected to membership since the last published list:—

Members

A. E. Bristow
G. H. F. Brown
R. F. Bulstrode
F. J. Frederick
W. W. Greenfield
L. Massey-Hilton
C. F. Hodson
P. B. Hovell
P. W. Howes
F. Jaques
G. H. M. Miles
J. V. Roberts
R. G. Robertson
J. E. Russell
A P. Thurston
I. Torbe
A. Vines
W. Welton
G. H. C. Willins

Associates

J. S. Fay
O. Hill
F. E. A. Mitchell
I. Roberts
J. de Milt Severne
R. I. Walton
R. W. Washer
W. A. R. Weaver

Graduate Members

O. V. Brooks
C. C. Cooper
I. H. Endean-Miller
G. S. Fletcher
W. A. Kuipers

Membership continues to grow steadily, having now passed the 150 mark. Members are reminded, when renewing their membership, that they may introduce new members with suitable qualifications, to the Association. Application forms for this purpose may be obtained by writing to the Secretary at Finsbury Circus House.

PUBLICATIONS COMMITTEE

This committee has now been formed, its function being generally to co-ordinate the activities of the Association concerning all matters relating to literature and the Library etc.

In particular its immediate function is to be responsible for the publication of the Association's bulletin at the desired intervals.

The Members are:—
E. G. Smettem (Chairman).
M. J. B. Stoker.
B. H. Arkell.

In addition, another member, H. Roberts, has kindly offered his assistance and this will be co-opted as soon as the Association is in a position to open its Technical and Semi Technical Library.

The Committee's immediate task, namely that of publishing this bulletin, is one which calls for no small amount of thought and careful preparation. Every effort is being made to maintain, and to improve upon the present standard, and in this connection members can be of great assistance in offering their criticisms. It should be borne in mind that some restriction in these early stages must be expected, due

partly to financial reasons and partly to the present day difficulties in printing. However, constructive suggestions will be very welcome and should be sent to:—

The Chairman,
Publications Committee,
at the offices of the Association.

NAME SPACE ADVERTISEMENTS

In order to augment the tunds necessary to publish the Bulletin, the Council have inaugurated a scheme whereby the support of the aircraft industry and other interested bodies has been enlisted in the form of name space advertisements.

The Council would like to take this opportunity of thanking those firms who have already accepted the offer for their generous co-operation, and hope that others will follow suit. The first insertions of the advertisements have been made in this issue, and a space has been reserved for those firms whose blocks have not yet come to hand. These will be included as soon as they are received.

The first improvement which this support has enabled the Association to make will be appreciated when the next issue appears as a fully fledged Journal. This will then become the Official Technical Publication of the Association, and will be issued quarterly in June, September, December and March.

The Bulletin will thenceforth continue in the form of a news sheet, and will be issued from time to time as required.

HELICOPTER MEETING AT CHRISTCHURCH

At the request of Captain Frost, the Honorary Secretary of the Christchurch Science Club, a lecture was given by Mr. Kenneth Watson to the Club at Christchurch on Wednesday evening, the 15th January, 1947. Mr. Watson is a Founder Member of the Association and is Chief Mechanical Engineer of the Cierva Autogiro Company.

The lecture, entitled "Rotary Wing Development," was mainly historical in nature, dealing with such subjects as types of rotor hubs, control mechanism, vibration, power plant requirements and other mechanical problems encountered in the development of rotating wing aircraft. A number of lantern slides were shown and the lecture had a very enthusiastic reception by an audience of approximately 80.

The Association has had several other such requests for helicopter lectures in various parts of the country and it is thought advisable to compile a register of the members and material available.

Will any member who would be willing to comply with a similar request to deliver a lecture, please send details to the Secretary, together with a general outline of the subject to be covered, for consideration.

A HISTORICAL REVIEW OF HELICOPTER DEVELOPMENT

by Group Captain R. N. LIPTROT, C.B.E.

Lecture given on October 12th at Manson House, London, before the Helicopter Association and Visitors from the Royal Aeronautical Society.

INTRODUCTION BY THE CHAIRMAN

Before asking Gp/Capt. Liptrot to give us his lecture a few words of introduction may not be out of place. It would be difficult to think of anyone better qualified to talk on the subject of rotary wing history than Gp/Capt. Liptrot, as he has been intimately associated with the development of this type of aircraft for the past 20 years, and latterly in his official capacity at the Air Ministry, Ministry of Aircraft Production, and Ministry of Supply. It is probably correct to say that he has had inside knowledge of every project in this country as well as a good many abroad.

Gp/Capt. Liptrot is a member of our Association and his enthusiasm for rotary wing flight has shown itself in a practical way during the past two years during which time he has done quite a lot of solo flying on the R.4. helicopter.

I am quite certain that his personal interest and sympathy has done much towards the general advancement of the Art in this country.

Finally, on behalf of the Association, may I welcome those members of the Royal Aeronautical Society who are here this afternoon as our guests, and also the guests of our own members.

Group Captain Liptrot —

Before commencing my lecture, I should like to express my appreciation of the great honour which you have paid me in inviting me to give what is really the inaugural lecture of the Helicopter Association of Great Britain.

It is appropriate, I think, that in this first lecture, in order to pave the way to more advanced treatment of the problems, we should consider in simple terms the basic principles and make a historical review, examining early efforts to build helicopters and tracing their development up to the position which we have now reached.

Ever since man began to think for himself he has wanted to imitate the flying creatures and, with their example in front of him, it was natural that flapping or rotating wings should be amongst the earliest suggestions for flying machines. Even in mythology we have the story of Icarus who made wings which he fastened to his arms with wax. It will be remembered that he flew too close to the sun, the heat from which melted the wax so that his wings fell off and he was hurled to his death. Thus we have the first recorded case of muscular flight and, at the same time, the first structural failure in a flying machine.

The problem of direct lift flight and, in particular, that of the helicopter, i.e. that type which derives its lift control, and propulsive thrust entirely from rotating wings, has intrigued inventors throughout the centuries and has perhaps attracted more attention than any other phase of the design of the heavier-than-air craft. It is very significant that when man first thought of flight he

thought in terms of direct lift, i.e. in rising vertically from the ground, remaining motionless at a desired height and then descending again vertically. Going places when once in the air was, in his mind, quite a secondary requirement. Even the Wright Brothers and others who are now famous aeroplane designers built their first models with this same idea in view, but they and many others who worked long and earnestly on the problem had little or no success. Then came the realisation that a suitably shaped surface propelled through the air would create lift, and the fixed wing glider, and the aeroplane, which is a power driven fixed wing glider, were developed. Our whole conception of flight thus became reversed for now, instead of rising into the air and then going forward, we were wholly concerned in going forward at a sufficient speed to rise and maintain ourselves in the air. This diversion, and it was a diversion, gave us the simpler solution of the aeroplane whose characteristics were sufficiently satisfactory to attract the finance which was necessary for its development. The aeroplane, of course, has made enormous strides, but it still has and will always have the shortcoming of being critically dependent on speed. To their everlasting credit, however, ever since flight was first achieved, there has always been someone somewhere working on the problems of direct lift and striving towards our original idea of lift, stability, and control independent of forward speed. We are glad to record that many who were led away from the seemingly insoluble problems of the helicopter to the simpler powered glider, have now seen the light and are in the forefront of helicopter development.

Of all that band of pioneers, pride of place must surely go to Juan de la Cierva, who, although not concerned in helicopter development, none the less paved the way more than anyone else to the satistactory solution of problems inherent in the helicopter. It was he, who impressed as he was by the risks of loss of speed on the conventional aircraft, argued that while speed on the supporting surfaces was of course essential to flight, it was not essential to the aircraft as a whole. He thus divorced the velocity of the aerofoil itself from that of the aircraft, by hingeing his aerofoils to a rotating centre, so that they could rotate independently to create sufficient lift for sustentation. The idea, of course, was not new, since all rotating wing devices rested on the same fundamental idea, though not previously so clearly defined by other workers. In developing this idea, he rediscovered other features which are vital to the helicopter and which had been propounded earlier, though never satisfactorily applied in practice, namely flapping blades to compensate for the dissymmetry of forward flight, control by tilting the rotor thrust and the high parachutal value of aerofoils, autorotating at a small positive angle of incidence. His autogyro provided the missing link in the quest for our ideal and an instrument on which to study the aerodynamic and mechanical problems of the rotating wing type of aircraft. Such was his success that at any time after 1932, when the C.30 autogiro was demonstrated, we could have built a satisfactory helicopter if the urge to do it and the necessary financial backing had been available.

That then is the broad picture. First we had the aeroplane with its fixed wing and dependent on speed for sufficient lift to support itself in flight, and with engines and propellers for propulsion, and separate organs for stability and control.

From this we had the transition to the autogiro with rotating wings, deriving its control from its rotor but still dependent on a certain amount of forward speed for its lift, though not subject to loss of control at low speeds. Finally, we have the complete co-ordination of all the essentials for flight in a rotating system, power driven for propulsion and lift, and convertible by pitch reduction to the autogiro for emergency landing. Thus we have the helicopter which was man's original conception of flight, but which was only reached through the intermediate development of the aeroplane and the autogiro.

Let us now trace this development. Even as long ago as the fifteenth century we find Leonardo da Vinci devoting several years of his life to the study of bird and mechanical flight, and he has left in his notebooks many sketches showing flying machines. Of particular interest is a design showing an aircraft consisting of a lifting screw driven about a vertical axis.

The first helicopter to fly was only a toy, the wellknown Chinese flying top, and the first helicopter to fly in the Western Hemisphere was a rather similar model, little more than a scientific toy, which was shown before the Academie des Sciences in 1784 by Launcy and Bienvenue, and since that time literally thousands of projects have been proposed by inventors all over the world. The Patent Offices of all countries are full of helicopter specifications, the greater part of them, unfortunately, based on faulty physical principles and obviously impracticable.

The direct lift aircraft is a heavier-than-air craft, which is able to lift itself and some useful load off the ground in still air, which can hover motionless over a given spot and descend vertically under its own power and, in particular which can make a safe descent in the event of engine failure. In addition, it must be able to move horizontally at the will of the pilot at a satisfactory speed, and it must be controllable and stable under all conditions of flight. The possibilities for the practical use of such an aircraft are obviously far reaching and they have excited the imagination of both laymen and technicians. The helicopter, that branch of direct lift aircraft with which we are concerned in this paper, is, in common with all rotating wing machines, the safest of all flying machines. This is so, not only because it cannot be stalled in the ordinary sense of the term, i.e. in that loss of forward speed only results in sinking on a level keel, but also because in conditions of low visibility use can be made of its very low minimum speed. So long as power is available a landing can be made in any clear space but little in excess of the rotor diameter and, in the event of a forced landing due to engine failure, a safe descent is still possible in to a restricted area.

It is in the required characteristics mentioned earlier, namely horizontal translation, stability and control, that the real difficulties of the problem lie, and very few of the earlier inventors in this field of flight appear to have seen the problem as a whole. In most cases they appear only to have considered the requirement of obtaining sufficient lift to sustain the aircraft. As long ago as 1904 Colonel Renard read papers before the Academie des Sciences in which he developed the theory of lifting screws to quite a considerable extent, and formulated the correct relationship between horsepower required, weight to be lifted and airscrew dimensions. Today, with our present knowledge, any competent propeller designer could provide a

PASSAT flapping wing

MOINEAU paddle wheel

The Sikorsky R.5

The Doblhoff jet helicopter

rotating system to give adequate lift for hovering flight.

As we have seen, the desired characteristic of hovering flight demands aerodynamic surfaces which have a velocity independent of the forward speed of the aircraft as a whole, and we have three main possibilities:—

1. Ornithopters in which the wings flap or oscillate.
2. The type in which the aerofoils are mounted like the blades of a paddle wheel.
3. The type in which the lifting system consists of blades attached to a hub rotating about a substantially vertical axis. This type has always held the field and has at last given us entirely practical helicopters capable of being put to practical use. It is this type which we shall discuss in what follows.

Let us now look at the special problems.

TRANSLATION.

In horizontal motion with a system of rotating aerofoils, the difficulty arises that the surface, which at any instant is advancing into the relative wind, has a higher velocity than the retreating surface and, therefore, exerts a greater lift. In the absence of special arrangements, this inequality of lift gives rise to an inconvenient overturning moment. Several arrangements have been proposed to overcome this difficulty.

(a) The cyclic change of resultant blade velocity can be avoided by arranging for a cyclic change of blade velocity, so that when advancing the blade would have a smaller angular velocity than when retreating. Such a method, however, involves excessively high angular accelerations and the solution is impracticable.

(b) Variable blade area or telescopic blades which can be retracted on the advancing side and extended on the retreating side. This method again is obviously impracticable.

(c) The use of pairs of systems rotating in opposite senses, the pairs being either superimposed, side by side, or in tandem.

(d) Other schemes assume constant angular velocity and, consequently, a cyclically changing relative velocity in forward flight, but propose to compensate by means of a cyclic change in blade characteristics governing lift, e.g. by flaps or similar means.

(e) A cyclic variation of blade angle or what is commonly called "feathering". The disadvantage of this method is that it involves rigid blades and the structural problem is made more difficult by the heavy periodic bending moments which it imposes at the blade roots, both in the flapping and drag senses.

(f) By blade flapping. The principle of the flapping blade was described in very early helicopter patents, but it was only when Cierva rediscovered it and applied it to his autogiro that its importance in the achievement of practical flight with rotating wings was appreciated.

It has the merit not only of suppressing the overturning moment caused by the aerodynamic dissymmetry of forward flight, but it also suppresses vertical bending moments at the blade roots and it minimises the effect of gusts on the aircraft. In point of fact, the suppression of the overturning moment is not complete, owing to the inertia of the blades which so influences the motion of the blade about the flapping hinge, that

the almost complete suppression of rolling in forward flight is accompanied by a pitching moment. This, however, is in point of fact beneficial, since flapping produces pitching of the aircraft due to the backward inclination of the lift vector, and, since flapping increases with forward speed, the aircraft becomes more tail heavy with increasing speed. Flapping, therefore, contributes to longitudinal stability.

Nearly all early helicopters used pairs of rotating systems, though since the advent of the autogiro the common form has been a single rotating system with articulated blades. Feathering blades have been used with some success and they and lift controlling devices at the blade tips are beginning to be developed once again. Feathering blades, indeed, are becoming of much greater interest. One of the disadvantages of flapping is that it introduces a dissymmetry in the plane of rotation. As a result of the tilt of the tip path plane with respect to the axis of rotation due to flapping and the upward coning of the blades, there is a geometrical dissymmetry in the plane at right-angles to the axis of rotation. This makes it necessary to introduce a drag hinge which, together with the flapping hinge, constitutes a universal joint. The natural frequency of oscillation about the drag hinge makes it necessary to introduce some form of damping, and either friction or hydraulic dampers have commonly been used. This damping, however, restricts the freedom of movement otherwise provided by the universal joint and periodic bending moments are re-introduced at the blade root. There is no such dissymmetry with a feathering rotor and so no drag hinge is necessary. The introduction of the drag hinge, which gives an additional degree of freedom of oscillation for each blade, has probably been responsible for more vibration troubles than any other step taken during the development of the rotating wing, and it may be that if the same amount of development work had been applied to feathering blades, instead of flapping blades with a drag hinge, many of the troubles which have delayed the development might have been avoided.

It should be pointed out that even with flapping blades, it is possible to maintain symmetry in the plane of rotation by mounting the hub on a universal joint and allowing the axis of rotation to tilt with the tip path plane, so that the axis of the hub and of the tip path are always coincident.

CONTROL.

In early helicopters control was sometimes sought either by surfaces hanging in the downwash from the rotors; by differential changes of blade angles between the pairs of rotors, causing differences in the lift of the individual rotors; by a cyclic change of blade angle which gives control by tilting the lift vector in the appropriate sense by tilting the whole rotor in the desired direction, or by variable pitch airscrews or rotors mounted about appropriate axes. The only one of these methods which is poor is the first one, since it not only introduces extra weight and drag due to the surfaces and the structure necessary to support them, but it is ineffective when the rotor is in autorotation in the event of power unit failure, since the air flow over the surfaces is then in the opposite direction, and the pilot's controls become inverted. All the other methods are in use in practical helicopters which are now flying, the only new method being that of cylcic variation of the lift characteristics of the blade by lift

increasing devices, such as flaps, instead of the cyclic variation of blade angle.

STABILITY.

The subject of the stability of helicopters is far too large a subject to deal with in a paper of this character and a whole series of papers could be devoted to this one subject. I shall content myself merely with pointing out any special features on the helicopters which I shall describe, which have a bearing on the stability problem.

ANTI-TORQUE CONTROL.

Whenever we have a rotor driven by an engine through gearing, we have a torque reaction which would result in the fuselage turning about the rotor axis in a direction opposite to that of the rotor itself. The methods used to overcome this torque reaction are characteristic, and they afford a means of classifying helicopters which I shall use in drawing a historical picture of the development.

The expedient of employing two rotors rotating in opposite senses is perhaps the simplest of all means of dealing with torque reaction, and it has been used on many helicopters. It has the merit not only of balancing the torque reaction from the individual screws, but also of eliminating the rolling moment in translation. There are several possible configurations of pairs of rotors all of which have been used from time to time. Up to the size within which we can build a practical rotor, the single rotor is the most attractive though it introduces special problems of its own in arranging for torque balance.

The alternative methods which have been used for balancing rotor torque are presented in what follows, and photographs of representative aircraft are reproduced.

1. **Twin Superimposed Co-axial Rotors.** Examples are:—

(a) *Breguet*. Even so long ago as 1907, Monsieur Louis Breguet built a helicopter with four lifting screws each consisting of four biplane blades. So far as I am aware, this was the very first helicopter which could lift itself and its pilot. In 1931 Breguet, who in the meantime had become famous as a builder of conventional aeroplanes, returned to the helicopter and, in collaboration with Monsieur Dorand, he built another also with two co-axial rotors. He achieved considerable success and the aircraft made manv flights both in hovering and in translation up to a speed of some 50 m.p.h.

(b) *Berliner*. In 1905 Emile Berliner in America had tried to build a helicopter with two co-axial rotors but without any success. In 1920 he and his son Henri built and flew another of the same type, which, however, was lacking in stability and control. Three years afterwards the son built yet another. This aircraft was derived from a Nieuport monoplane by replacing the wing by two lifting screws, one on each side. The elevator was supplemented by an auxiliary propeller mounted on a vertical axis and lateral control was effected by vertically movable flaps in the downwash from the rotors. Little success was achieved, though during its flight trials the aircraft rose to a height of some 2 ft. and made hops up to 30 yds. at a speed of some 30 m.p.h.

(c) *Pescara*. Between 1920 and 1925 Pescara constructed four helicopters all of the same general type. They had two superimposed co-axial lifting systems, the early ones with six

An early Breguet machine

The Focke F.A. 223

The Piasecki P.V.3

The Flettner Fl.282

and the later ones with four biplane blades which could be warped either all blades together or cyclically. By warping the blades at the moment when they passed through any desired azimuth, the lift vector was displaced in azimuth towards the side where the blade angle was increased and so a moment giving control in the desired direction was produced. The same principle was used for inclining the axis of the aircraft, in order to obtain a horizontal component of the total lift to provide translation in the desired direction. By warping the two rotors differentially he obtained a yawing moment to turn the aircraft in the desired direction. Pescara was also one of the first to understand the principle of autorotation and, with the blades at a small angle of incidence, his aircraft were able to descend freely and under control in the event of engine failure. It will be seen that these helicopters satisfied practically all the desiderata which I have mentioned. The main fault, as in all other twin superimposed systems, was that they were unstable.

In 1924 the second of these helicopters put up very interesting performances, flying up to 700 yards in horizontal flight and staying in the air up to a maximum of 12 minutes.

(d) *Karman Petrosczy*. This helicopter was produced during the 1914-1918 war to replace kite balloons for observation purposes. Its construction was carried out under the direction of Professor von Karman, the wellknown aerodynamic technician, and the lifting screws were designed by Herr Asboth whose work will be described later.

It consisted essentially of two superimposed wooden propellers, driven in the first place by an electric motor and subsequently by three 120 h.p. Le Rhone engines. No control was provided and stability was assured by a 3-cable mooring system. With Le Rhone engines the weight was 3,520 lb. of which 660 lb. was useful load, and the screws were 19.8 ft. in diameter. It rose to heights up to 150 ft. and stayed in the air for considerable periods, the maximum being one hour.

(e) *D'Ascarnio*. This helicopter created history in 1930 by being the first to make a record recognised by the Federation Internationale in the Helicopter class. The following performances officially recognised by the F.A.I.:—Vertical ascent to 60 ft., a straight flight of 560 yards, a duration of 8¾ mins., and a closed circuit over 1 kilometre.

The aircraft had two superimposed co-axial 2-bladed rotors each of 39 ft. diameter turning in opposite senses. The blades were articulated, being free to flap by being mounted on a horizontal hinge, and they also had freedom in pitch. They were stablised by a small tailplane at the blade tip and their angle was controlled by an elevator. The aircraft also had three small auxiliary variable pitch screws, one vertical on one side to provide yawing control, the others horizontal—one at the side to give lateral control and the other on the tail for longitudinal control and to tilt the aircraft for forward flight. The aircraft weighed 1,680 lb. and the engine developed 95 horsepower.

(f) ***Asboth.*** Asboth, to whom I have referred earlier in connection with the design of the lifting screws of the Karman Petrosczy helicopter successfully built and flew four helicopters. The fourth aircraft, built in 1928, had two wooden screws mounted co-axially. Control was provided by six surfaces movable about horizontal hinges and hanging in the downwash from the screws. I had the great pleasure of personally carrying out flight trials on this helicopter and I found that it was stable and controllable, could make a vertical ascent at about 300 ft. per min. and could hover indefinitely. The maximum height attained during trials was about 100 ft.; the maximum distance some 3,000 yds. at a speed of the order of 12 m.p.h. The aircraft was very crude indeed, but it achieved considerable success, the one feature which was lacking being that no provision was made for a safe landing in the event of engine failure. Asboth, however, was convinced that if he had had a free wheel incorporated, his special fixed pitch screws would have remained in autorotation and that a safe rate of descent would have been achieved. The aircraft weighed 1,080 lb., the screws were each 14 ft. in diameter and the engine developed about 110 h.p.

2. **Pairs of Rotors Side by Side.**

(a) *De Bothezat.* In 1921 de Bothezat built the first helicopter ordered by the U.S. Army Air Force. It was a very crude affair but, nevertheless, it carried out many flight trials, and in 1923 it actually lifted a pilot plus passenger. It was too heavy, very complex and unstable.

(b) ***Oemichen.*** In 1920 Oemichen constructed a helicopter which consisted of a fuselage carrying an engine driving two lifting screws each of two blades. The sustaining screws were 20.8 ft. in diameter, the engine developed 25 h.p. and the total weight was 750 lb. The aircraft was not able to lift itself and a small balloon was added, therefore, partly to give the necessary extra lift and partly to stablilise it. With the balloon fitted a number of elementary flights were made, the maximum height reached being 16 ft. and the distance in horizontal flight 60 yds. Following on this early attempt, Oemichen built a second helicopter consisting of four lifting systems with five auxiliary variable pitch airscrews for control with two propellers for propulsion and an additional screw in front for yawing control. This helicopter is historic because in May, 1923, it successfully made several flights of from 600 to 700 yds., hovered for 5 minutes over a fixed point and in May, 1924, was the first to cover an officially observed closed circuit of one kilometre. The maximum performance actually realised was a flight of 14 mins., a maximum height of 50 ft. and a maximum distance of 1,850 yds., carrying a useful load of 440 lb. in addition to the pilot.

(c) *Focké.* The first satisfactory helicopter was the Focké Achgelis type 61 which was demonstrated in Berlin in 1937. The blades were articulated and cyclic pitch control was used for longitudinal and directional control. For lateral control the angles of all the blades of one rotor were increased, while the angle of all the blades on the

other rotor was decreased. The aircraft weighed some 2,300 lb. and the engine developed 160 h.p. It held the following records recognised by the F.A.I.:—

Height, 8,000 ft.
Time, 1 hr. 20 mins. 50 sec.
Speed, 76 m.p.h.
Distance in closed circuit, 50 miles.
Distance cross country, 143 miles.

In 1938 Luft Hansa had ordered a civil 6-seater helicopter from Focké and during the war this type was developed into a military type, the FA. 223. Its characteristics were:—

Empty weight, 7,200 lb.
Normal useful load, 1,300 lb.
Max. useful load, 2,300 lb.
Horsepower, 1,000 b.h.p.
Dia. of each rotor, 39 ft.
Max. speed, 110 m.p.h.
Cruising speed, 80 m.p.h.
Eudurance, 3 hrs.

During the war also Focké had commenced the design of a large weight carrying type, the FA. 284. This type was intended to carry armoured cars, small tanks, etc., across rivers and act as a mobile crane for lifting bridge girders into place.

Its estimated characteristics were:—

Horsepower, 2 BWM 801 engines each developing 1,000 h.p.
Dia. of each rotor, 59 ft.
Empty weight, 18,000 lb.
Fuel and oil, 1,560 lb.
Crew, 440 lb.
Max. freight load, 15,200 lb.
Total weight, 35,200 lb.

This project was abandoned, after a good deal of design had been done, in favour of the simpler alternative of building two FA. 223 lifting systems on to a common fuselage. This aircraft also was never built.

(d) *G. J. Weir, Ltd.* Quite independently of Focké and at about the same time a small single seater helicopter of the same general type as the Focké was built in Glasgow by Messrs. G. & J. Weir, Ltd., who were associated with the Cierva Autogiro Co. Their designer was Mr. C. G. Pullin. In 1939 they also built a bigger 2-seater aircraft with a Gipsy 200 h.p. engine. This aircraft flew successfully and was intended to be the basis of yet a bigger design to fulfil a definite operational duty. Unfortunately, owing to the war position, this project had to be abandoned.

(e) *Platt-le Page.* Following the success of the Focké Achgelis type 61, the U.S. Army Air Corps ordered its second helicopter from Platt-le Page. The aircraft the XRI was engined by a Wasp Junior developing 450 h.p. and weighed about 5,500 lb. Control, as usual, is by cyclic pitch control of the blades. The aircraft made its flight trials in 1943 but, in spite of many tests including several flights of quite long duration, it is not yet developed into an entirely satisfactory type, and official interest in America seems to be waning.

(f) *Landgraf.* A most interesting type with twin side-by-side rotors is the Landgraf. It is only a small single seater with a Pobjoy 85 h.p. engine and weighing 850 lb., being intended only as a laboratory aircraft to test out principles and to gain

experience on which bigger aircraft could be designed. It has a maximum speed of 135 m.p.h., cruising speed of 100 m.p.h. and an endurance of 1½ hrs. It differs from almost all other helicopters in that the blades are rigid and that instead of cyclic pitch change of the blades—a method which tilts the lift vector—the blades are fitted with ailerons at the tips. These ailerons are deflected cyclically, so displacing the lift vector in the required sense to give either the desired control or translation. The arrangement has the merit that the centre of gravity can be located even at 15% of the rotor diameter in advance of its axis of rotation, and that it is stable longitudinally.

Trimming for variation of centre of gravity position is simple and the response to control is positive without the lag which is characteristic of cyclic pitch control.

3. **Rotors in Tandem.**

(a) ***Florine.*** Very great interest was created at the Antwerp Exhibition of 1930 by the Florine Helicopter. In this aircraft the two rotors, as distinct from all other helicopters with twin rotors, turned in the same sense. The torque reaction was balanced by tilting the rotor axis one to one side the other to the opposite.

(b) ***Piasecki.*** Piasecki, a young American engineer, built a small helicopter of the same general type as the Sikorsky, and he achieved such success that he was given an order for a cargo helicopter the now well known PV3 by the American Navy Bureau.

The estimated characteristics of the aircraft are:—

Horsepower, 550.
Dia. of each rotor, 41 ft.
Empty weight, 4,300 lb.
Freight load, 1,000 lb.
Total weight, 6,400 lb.
Max. speed, 110 m.p.h.
Cruising speed, 84 m.p.h.
Endurance, 3½ hours.

This solution is of considerable interest, since it permits us to build bigger helicopters economically, by using two of the rotors complete with power units and transmissions from smaller types already developed. The configuration itself is also attractive, since it is stable longitudinally and permits longitudinal trimming over a wide range of movement of the centre of gravity.

4. **Two Intermeshing Rotors.**

About 1938 the Cierva Autogiro Co. and Dr. Bennett, their Chief Technician, had proposed that in the interest of reduction of size, weight and drag, the hubs of the side-by-side arrangement should be brought close together with an angle between the axes to ensure that the blade would not foul during flight. This type was never built in Great Britain, but the following examples have been built elsewhere.

(a) ***Flettner.*** During the recent war, Flettner in Germany constructed a small 2-seater with two intermeshing 2-bladed rotors, known as the Fl. 282. It was intended to operate from cruisers for observation purposes.

Its characteristics are:—
Engine, 140 h.p.
Dia. of each rotor, 39.5 ft.
Empty weight, 1,400 lb.
Gross weight, 2,200 lb.
Max. speed, 90 m.p.h.
Vertical rate of climb, 300 ft. per min.
Hovering ceiling, 1,000 ft.

(b) *Kellett.* The Kellett Co. in America, who were licencees of the Autogiro Co. of America, have also constructed an aircraft, the XR.8, with intermeshing rotors to which the name "Synchropter" has been given. Its estimated chracteristics are:—

Engine power, 250 b.h.p.
Empty weight, 2,140 lb.
Useful load, 650 lb.
Total weight, 2,790 lb.
Max. speed, 105 m.p.h.
Cruising speed, 85 m.p.h.
Hovering ceiling, 3,000 ft.
Max. ceiling in translation, 13,500 ft.

Kellett is also building a bigger aircraft, the type XR. 10, which is estimated to have the following characteristics:—

Engines, 2, each developing 525 h.p.
Dia. of each rotor, 65 ft.
Empty weight, 7,500 lb.
Useful load, 2,800 lb.
Total weight, 10,300 lb.
Max. speed, 125 m.p.h.
Cruising speed, 90 m.p.h.
Endurance, 3 hrs. (for increased duration auxiliary tanks are provided, increasing the endurance to 6½ hrs.).
Hovering ceiling, 6,000 ft.
Max. ceiling, 20,000 ft.

(Note.—In the other load case with normal fuel and maximum freight of 3,750 lb., the total weight is 13,500 lb.)

5. **A Single Rotor with Auxiliary Tail Rotor.**

As has been pointed out, the autogiro provided a major contribution to the development of the helicopter. The autogiro possesses all the characteristics required by the helicopter and, indeed, in its final form, of which the Cierva type C.40 and Hafner's Gyroplane are examples, it was in fact a helicopter for several seconds during take-off. For vertical take-off in these types, the rotor was over revved with the blades at a small angle, then the blade angle was suddenly increased and the aircraft jumped in true helicopter style. After the initial jump the blade angles were returned to the autorotative setting and the aircraft continued in flight as a normal autogiro.

It is not a matter for surprise, therefore, that the helicopters which so far have given the greatest success have been those like the Sikorsky, which have a single articulated rotor with an auxiliary rotor at the tail to provide torque balance.

This configuration is not new, since in 1925 von Baumhauer in Holland constructed a helicopter of this type but he used rigid blades and, although the aircraft was able to rise some few feet and to hover for periods up to 5 minutes, it never achieved really practical results.

Oemichen's third helicopter built in 1928 used a similar arrangement, though, in his case, he provided two lateral auxiliary propellers, one at the nose and one at the tail on opposite sides so as to obtain yawing couple rather than a moment.

(a) *Sikorsky.* It was left for Sikorsky to develop this type into a really practical helicopter and to create, not only in America but throughout the world, an enormous interest in the problems connectd with the helicopter.

In 1909 Sikorsky had designed a helicopter without any success and he turned to the conventional aeroplane, for which he is very well known. In 1938, however, he returned to the study of the helicopter. His first type had a single articulated rotor with three variable pitch rotors at the tail; one turning in the

vertical plane was to balance torque reaction, and the two others turning in horizontal planes were for longitudinal and lateral control. This type was entirely satisfactory and it broke all existing world records. In spite of this success, it was in fact only a flying laboratory, and during development the two horizontal auxiliary rotors were replaced by a single rotor for longitudinal control, and cyclic pitch control was introduced for lateral control. This change brought about such a great improvement in the flying characteristics of the aircraft, particularly in its control, that in the the final form cyclic pitch control was used for both longitudinal and lateral control. By the end of the war Sikorsky had built three different types in addition to the laboratory aircraft, known as R.4, R.5 and R.6, of which the two latter were put into full scale production.

The R.4, which is probably the best known of all helicopters today, is a 2-seater with an engine developing 185 h.p. Its normal flying weight is about 2,600 lb. including a useful load of 550 lb. Its maximum speed is 82 miles per hour and its cruising speed 70 m.p.h. The diameter of the main rotor is 38 ft. This aircraft, which is largely experimental, is under powered and it can only hover at a height comparable with its rotor diameter, i.e., within the ground cushion. In translation, however, its ceiling is of the order of 9,000 ft.

R.6.—This is only a refined version of the R.4. Its characteristics are:—

Engine, 240 h.p.
Normal weight, 2,650 lb.
Useful load, 585 lb.
Max. speed, 94 m.p.h.
Cruising speed, 80 m.p.h.
Main rotor dia., 38 ft.
Max. ceiling in translation, 15,000 ft.

R.5.—This is a bigger aircraft, the first one ever to be designed to fulfil an operational function, i.e., to carry hydrostatic bombs for operation against submarines, and as a means of protecting convoys. Its characteristics are:—

Engine, 450 h.p.
Normal weight, 4,950 lb.
Useful load, 1,100 lb.
Endurance, 4 hrs.
Max. speed, 106 m.p.h.
Cruising speed, 90 m.p.h.
Hovering ceiling, 2,000 ft.
Max. ceiling in translation, 14,500 ft.
Main rotor dia., 48 ft.

Later Sikorsky modified the R.5 installing a bigger engine developing 500 h.p. and with a cabin accommodating six passengers. In this case, he returned to his original idea of a second horizontal tail rotor for longitudinal control. He did this, not only to improve longitudinal control and stability, but also to give a means of trimming the aircraft for variations in c.g. position. It is understood that Sikorsky has abandoned this type and instead is building a straightforward civil version of the R.5, i.e., with normal cyclic pitch control and a single tail rotor for torque balance. It is this type, known as the S.51 which has recently been awarded the American Civil Airworthiness Certificate.

(b) *Bell.* Another interesting American design of the same general configuration is the Bell which has several important characteristics. Contrary to almost all

other helicopters, this type has a single rotor of 2 blades only, the blades being rigid. This type of rotor suffers from severe vibration. In the Bell type this is not permitted to reach the fuselage and passengers, since the rotor and power unit are mounted on flexible rubber mountings. The rotor is mounted universally on a pylon and, as the method of cyclic pitch control is used, the hub tilts with application of control. The special characteristic of the rotor is the means adopted for stabilising. This consists of a weighted rod at right angles to the blades and mounted on a horizontal axis. This rod is connected to the cyclic pitch control mechanism and, acting as a gyroscope, controls the attitude of the rotor in spite of any inclination of its axis, while at the same time, the cyclic pitch control can still incline the rotor for control purposes at the will of the pilot. The control and stability of the Bell helicopter are reported to be very good indeed. A small 2-seater of this configuration is being put into production and has obtained an American Certificate of Airworthiness, and a bigger type weighing 4,800 lb. with an engine developing 450 h.p., accommodating a pilot and four passengers, is also undergoing flight trials. Information on this aircraft is not complete, but it would appear that with a bigger rotor considerable vibration troubles are being experienced.

(c) *Hafner.* Many years ago, Hafner constructed a helicopter with very little success. From flight trials on this aircraft, he appreciated the control problems facing the helicopter designer and he turned to the autogiro as the simplest rotating wing type on which to develop his ideas. He arrived at his well known Gyroplane which used cyclic pitch control and gave extremely good performance. He has now returned to the helicopter and is designing a 4-seater with an engine of 450 h.p. Its most interesting characteristic perhaps is that, as in his Gyroplane, the blades are mounted on a group of torsional rods which not only give a frictionless feathering hinge, but also give a torsional restoring moment which stabilises the blade.

(d) A variant of this general type has been proposed by Dr. Bennett, in which the auxiliary tail rotor is arranged to autorotate in the downwash from the main rotor. In this way, perhaps, we might eliminate the power loss which is associated with the tail rotor of the Sikorsky configuration.

6. Single Rotor with Off-Set Tractor Propeller.

This type is a variation of the general Sikorsky configuration which has been proposed by Dr. Bennett. In this arrangement the propeller, which is used to balance torque reaction, is mounted as a tractor on a stub wing at the side of the aircraft. Power for balancing torque reaction in cruising flight is thus reduced and the torque correcting propeller also contributes tractive forces for translational flight. The efficiency of the aircraft in flight is thus improved and the price paid is that the power for compensating torque reaction is increased during hovering. As the proportion of the total flight which is spent in hovering is relatively small, this loss of power is of little account.

As this type of helicopter is half-way between the autogiro and the true helicopter, it has been given the name 'Gyrodyne.' The main points in favour of this configuration are:—

(a) Because it uses the torque correcting thrust for forward propulsion, it eliminates the power losses inevitably associated with all other methods of torque balance.

(b) The rotor disc is little if ever forwardly inclined, even at top speed, and there is thus no need to increase the blade angles to compensate for the reduced angle of attack which is caused by the axial flow through the rotor. This has two very definite advantages.

  (i) The blade angles are always within the autorotational regime, so that autorotation is automatic in the event of power unit failure.

  (ii) It eliminates the possibility of blade tip stalling and the dissymmetry associated with a tilt of the tip path plane, so that while a true helicopter becomes progressively rougher and less efficient with increasing speed, the Gyrodyne remains as smooth and as efficient as the autogiro under all flight conditions.

It can be disclosed that a 4-seater Gyrodyne is at present under construction, but it is not permissible to give details.

7. A Single Rotor with Surfaces in the Downwash from the Main Rotor.

About 1938 Hafner was designing a helicopter with a rotor of low solidity and high rotational speed, in which the fuselage was of twisted aerofoil shape in order to provide torque balance. Owing to war conditions, this type was not completed.

8. A Single Rotor with Jet Reaction at the Tail.

An example of this type of helicopter is one designed by Mr. C. G. Pullin and constructed by the Cierva Autogiro Co., which is now undergoing its trials. Quite apart from the jet reaction at the tail, this type is of interest because control is obtained by tilting the entire hub which is mounted on a spherical joint of the "constant velocity" type, and that the articulations are of the type with two inter-coupled hinges so arranged that any tendency of the blades to flap is converted into pitch change. This arrangement was proposed in order to get a rotor which would be automatically stable in gusts.

9. A Single Torqueless Rotor.

The most attractive single rotor helicopter, because of its mechanical simplicity, would be one with jet reaction motors at the tips of the blade, because, in that case, there would be no torque reaction and no need for any torque balancing device which inevitably involves some loss of power. It is also advantageous in that it eliminates clutches, free wheels, gearing and transmissions, and so reduces the bare weight of the aircraft.

One of the first to realise the advantage of this type was Monsieur Isacco, but, in the absence of jet reaction devices, he was forced to use reciprocating engines with propellers mounted on the blades. In his type, each blade was essentially a small monoplane with its own aerodynamic controls and power units mounted universally on a hub, and so constrained to move in a circular path. Isacco called this type the 'Helicogyre.'

The first aircraft which he constructed was a single seater with a 2-bladed rotor 41 ft. diameter, each blade carrying a small engine developing 30 h.p. I had the great pleasure of personally carrying out

flight tests on this aircraft and I can say that, weighing 1,320 lbs., it was just capable of hovering close to the ground. I was not able to attempt free flight in the open, but my tests were made in a large airship shed, and with quite a small forward velocity I was able to get the aircraft airborne, when it proved to be stable and controllable. Isacco, in point of fact, never intended this type to be a true helicopter, i.e. capable of hovering, but rather postulated that it should always have a small forward speed which, of course, greatly increases lift efficiency and, for this reason and with the same underlying idea as in the Gyrodyne, he fitted a forward tractor engine and propeller, so that the rotor axis should always remain vertical.

Another aircraft of this type was built in Great Britain in 1929 this time with a 49 ft. diameter rotor with four blades each with an engine of 40 h.p. The total weight was 2,420 lb. and it proved to be just capable of supporting itself close to the ground. Its trials, unfortunately, had to be terminated because the engines would not run for more than a few minutes because of difficulties of lubrication and carburation, due to the intense centrifugal field in which they were operating.

One has to admit, I think, that Isacco was in advance of his time and that if he had had satisfactory power units, his type could have flown satisfactorily.

Nagler-Rolz. During the war Nagler and Rolz in Austria built a baby helicopter of this same general type. It had a 2-bladed rotor 13 ft. diameter, each blade carrying an 8 h.p. engine. The gross weight including 220 lb. for pilot and fuel, was 312 lb. The designed forward speed was 50 m.p.h. and the estimated vertical climb 480 ft. per min.

During the war many inventors have tried to use jet reaction, but the only aircraft within my knowledge which has flown successfully is the Doblhoff, also constructed in Austria. The principle employed here was to drive a compressor from a normal reciprocating engine. The compressed air was mixed with petrol vapour and the gases ducted to the blade tips where they were burned in combustion chambers. This aircraft had undergone some 25 hrs. testing in hovering flight and made a few flights in translation up to some 20 m.p.h. The main disadvantage was that the fuel consumption was prohibitively high. Until it was found possible by development to bring down the fuel consumption to a more reasonable level, it was Doblhoff's intention to fit a propulsive screw which could be clutched in as required. The jet would then only be used for landing and take-off as a helicopter, the aircraft being flown as an autogiro in cruising flight.

10. **Oscillating Rotors.**

A method of driving rotors which would be free from the usual torque reaction was suggested some years ago by Count Korwin. He proposed a pair of articulated rotors mounted co-axially and in which the two rotors were oscillated along their axes. The claim was made that not only would this provide a drive for the rotors, but that the flapping of the rotors would give an increased contribution to lift. This, of course, is not true, and the method is not likely to be practicable though it is of interest as showing another method for a torqueless drive.

In proposing a vote of thanks for this Inaugural Lecture, The Chairman, Mr. H. A Marsh, felt all would agree that it was a very good beginning to the Association's activities. The Sikorsky film was then shown.

HELICOPTER RESEARCH AND DEVELOPMENT

by C. G. PULLIN, F.R.Ae.S., M.I.Mech.E.

Lecture given on November 9th at Manson House, Portland Place, London, before Members of the Helicopter Association and Visitors from the Royal Aeronautical Society.

INTRODUCTION BY THE CHAIRMAN

Ladies and Gentlemen, I feel that an introduction to our lecturer this afternoon is hardly necessary, as I am sure he is well known to most of you, but perhaps one or two may not be so well acquainted either with his background, or his work in rotating wing aircraft.

Mr. Pullin is the Managing Director and Chief Designer of the Cierva Autogiro Co. Ltd., a Founder Member of our Association, a Fellow of the Royal Aeronautical Society, and a Member of the Institute of Mechanical Engineers. He has been actively engaged in the research and development of rotary wing aircraft since 1932, but his interest in aviation goes back to pre-1914 when he learnt to fly at Brooklands in the good old days. He has been engaged in engineering for about 30 years, covering in this time, several of its different branches.

After the lecture, Mr. Pullin will show a short film depicting various stages of test work on rotary wing aircraft, and if time permits, a short period will be devoted to answering questions. Some of these Mr. Pullin hopes to be able to answer here, but others may require written answers.

May I take this opportunity of welcoming our guests this afternoon who, I feel sure, will be well rewarded for coming along.

Mr. PULLIN:—

Mr. Chairman, Ladies and Gentlemen,

I must first thank the Chairman for his kind introduction, and I should also like to take this opportunity of according my appreciation of the opportunity given to me to speak before Members of the Association and visiting Members of the Royal Aeronautical Society.

As some of you are aware, I have been associated with rotating wing aircraft since early in 1932, commencing of course with the Autogiro. As I think I may claim to be the misguided individual mainly responsible for the first practical research and development programme of helicopters in Great Britain, I feel somewhat justified in giving a relatively brief resumé of the work with which I have been entrusted over the past fourteen years.

As regards the Autogiro or Rota plane, so much has been written from time to time that I propose to confine this lecture to the helicopter, but before doing so, I should like to express my appreciation of the splendid work of the late Juan de la Cierva which has enabled the helicopter to become a practical entity in the field of aviation. It is also a fitting occasion to mention the valuable support given to Cierva by Mr. James Weir, which put the development on a sound basis. Mr. Weir has also contributed many

important mechanical improvements and his keen technical interest represents a monument of encouragement to all engaged in the particular "art." I must also include Mr. Harold Pitcairn, who formed the Autogiro Company of America and is responsible for the introduction of rotating wing aircraft in the U.S.A. The latest example of The Autogiro Company of America, is the helicopter built under licence by the G. & A. Aircraft Incorporated, branch of the Firestone Tyre & Rubber Co. Inc .

There appears to be a general impression that the development of the helicopter has received more attention in the U.S.A. than in this country. Whilst this may be true from the purely practical aspect, I will leave it to my audience to formulate their own opinion at the conclusion of this Meeting as to whether we have lagged behind in the scientific investigation and engineering development.

The previous lecturer, Group Captain R. N. Liptrot, C.B.E., delivered a most interesting talk on the Historical Development of Helicopter Aircraft, and from which it was quite apparent that no one particular configuration could be considered as a pre-eminent solution to the problem of helicopter flight. There are, for instance, many arrangements of single and multi-rotor helicopters in practical use today, but all employ the same fundamental principle. Fortunately, as it now transpires. the lift derived from the downward acceleration of a mass of air did not form the subject matter of a valid patent, with the result that this principle of direct lift is today exemplified in so many forms.

In the early days of aviation, the helicopter received much attention by scientists and inventors throughout the world, and it was soon established that no great difficulty would be experienced in obtaining substantial lift. However, owing to the unsatisfactory power weight ratio of the power plant, not to mention the relatively heavy power unit installation and transmission system, the fullscale aircraft then constructed were only capable of "swimming" a few inches above the ground. Subsequent development of the Internal Combustion Engine, also the use of special materials, the power weight ratio of the complete aircraft was so much improved that there appeared to be adequate lift to rise some hundreds of feet from the ground. Following upon this advance, the development was hampered by the state of reliability of the prime mover and transmission. Here again the excellent methods of the A.I.D. applied to the control and manufacture of aircraft engines and components, resulted in reducing this hazard to a negligible quantity. Nevertheless, the potential danger still remained until the principle of autorotation came to the rescue (thanks to the work of the late Juan de la Cierva and his Associates), which made it possible to continue the development of this most attractive form of aerial vehicle. I presume it is common knowledge that in the event of mechanical failure, the helicopter rotors will cease to revolve and the machine will plunge to earth in a most unsatisfactory manner. By making provision for a change of blade angle to that necessary for autorotation, it becomes possible to glide safely to earth or even make a vertical descent. The latter, even in the hands of a really bad pilot, would not mean more

The Weir W.5. Helicopter on the ground and in flight.

than a visit to the hospital rather than a permanent one to the Cemetery. As regards the actual change of blade angle, this should be qualified by saying, that with certain projects, such as the ultra high speed rotor, it may be unnecessary to change the blade angle as the incidence for helicopter operation is of such a low order as to be suitable for that of autorotation, especially the type of helicopter blade that has a built-in wash-out of incidence as from root to tip.

From the foregoing remarks, it will be readily understood that an experimenter in the " art ", with existing data at his disposal, can build a rotor to give sufficient lift for his purpose, but having done so, becomes a menace to himself and to any person or persons within the vicinity of his testing ground. I am, of course, referring to the difficulties of stability and control of the aircraft when airborne.

At this stage I feel it necessary to apologise for this rather lengthy introduction, but there are, I believe, some fortunate members of the Association in the audience this afternoon, that have joined the development at a comparatively recent stage. In going back over the

Weir W.5. Helicopter flying backwards.

past years, I realise, as one of the pioneers engaged in the development of this type of aircraft, the grave risks undertaken by Members of my Staff and also my first Test Pilot. The anxiety to the Designer when the machine first leaves the ground and perhaps flies round the field for the first time, is very great. Minutes seem to be as hours and the relief when the aircraft safely lands must be experienced to be fully appreciated.

On one occasion in 1938, the small 50 h.p. side-by-side Weir W.5, inadvertently discarded a rotor blade which sailed along over the heads of the well ordered ranks of some 100 R.A.F. recruits, fortunately without damage to anything but the aerodrome and the blade itself. I feel sure, had Julius Caesar witnessed the occurrence, knives on chariot wheels would have become obsolete. Again, when testing for maximum speed, which by the way was in the order of 70 m.p.h., the pilot attempted a banked turn at the end of the straight run but instead the aircraft decided to make a power-dive from 150 feet. The pilot operated every available control to pull the machine out before it hit the ground but his efforts being unsuccessful, resigned to await the unwanted but very necessary bump. To his surprise, and to the amazement of the few onlookers, the aircraft appeared to take advantage of the ground cushion effect, straightening out into a nice flat glide across the field.

On another occasion, when demonstrating the flying capabilities of the same machine, the tail wheel and oleo dropped off when on the fifth circuit of the football field at some 200 feet from the ground.

Weir W.6 Helicopter in flight.

The pilot was quite unaware that he had lost what would once have been considered as quite an important part of the aircraft, finally making the usual soft helicopter touchdown but at a silghtly increased ground angle to that for which the machine had been designed. With the larger edition of the same type, i.e., the Weir W.6, whilst hovering some 50 feet from the ground, one of the rotor blades broke away at the root end which incidentally caused much perturbation as the factor of safety was considered to be adequate.

The pilot and his passenger on this occasion made a wonderful tail slide landing, being finally ejected through the bottom of the fuselage. I believe the marks of their passage through the machine are in existence today, but not of course, on the airfield.

As a point of interest, I might mention that the Test Pilot's licence was subsequently endorsed for helicopter flight and it may therefore be put on record that outside of Germany he was, I believe, the first officially recognised helicopter pilot.

In conclusion of this introduction and before I proceed with perhaps some of the more interesting details of development, I must apologise for being unable to exhibit any colourful films of flight testing or demon trations, but on the other hand, most of the slides that will be shown on the screen, have in their development, merited the colourful remarks of those engaged in their conception and practical applica tion.

5. *Weir W.6 Helicopter in flight with Lord Tedder as passenger (1940).*

I will deal with the subject which seems to be pre-eminent in the minds of those associated with the " art " either as inventors, designers or practical operators. I refer to the problem of torque balance. In discussing a new helicopter project, the first question asked is, what method is employed for torque balance ? Why so much attention is focussed on this is rather curious, as the engine power expended for instance with the tail airscrew or even tail jet, is quite marginal. The interest perhaps is associated with the remote possibility of securing torque balance by some inceptive influence outside the aircraft or by a cunning arrangement of components to achieve the desired results at zero cost. A great number of ingenious schemes have been proposed, some even in practical form, but no satisfactory solution has been found

apart from the generally known and accepted examples as in use today. As most of you are aware, the necessity of torque balance is substantially eliminated by the use of multi-rotors, whether side-by-side, co-axial or star plan configuration. It will also be understood, that in the case of the Autogiro, the rotor being self driving under aerodynamic influence, does not produce any reaction in the body of the aircraft about the rotor or yawing axis. The same may be said of the helicopter rotor propelled by reactive thrusts from jets or slots formed in the rotor blades. Strange as it may seem, my recent experiments indicate that the complete elimination of rotor torque reaction is inadvisable, which will be gathered from particulars of tests to be described later.

In 1937, I proposed to the Directors of Messrs. G. & J. Weir, Ltd., licencees of the Cierva Autogiro Co. Ltd., that the Autogiro development work, with which I was entrusted, should be extended to the helicopter. The German Company of Focké Aghelis, licencees of the Cierva Autogiro Co. Ltd., were, at that juncture, making practical tests of a twin rotor, side-by-side helicopter. At the request of the Ministry of Aircraft Production, an endeavour was made to secure a duplicate machine for experimental tests in this country, but the price was prohibitive and delivery somewhat protracted. At my suggestion, Messrs. G. & J. Weir, Ltd., agreed to build a research helicopter and I received instructions to investigate the possibilities late in 1937. The first study was concentrated upon the two rotor superimposed arrangement, but the then apparent difficulties of securing unhampered blade articulation, or let us say fouling of rotor blades, appeared to be very severe. Control and stability problems were the main reason why the project was discarded. It will be noted that I evaded the difficulties of torque balance by the oppositely turning superimposed rotors. Having realised that the major problem was one of control and stability, the obvious solution was to place the rotors on either side of the fuselage. Turning in opposite sense would deal with the question of torque balance, so that control and stability could be studied in a more appropriate manner.

As I am now dealing with the subject of torque balance, which if not eliminated completely, is simplified by the use of multi-rotors, it would perhaps be fitting to briefly examine such types. There are many possible arrangements of multi-rotor helicopters and it is obvious that the twin side-by-side type can be re-arranged so that the rotors are fore and aft, i.e. the tandem arrangement.

6. Cierva two engine, three rotor, ten passenger or freight helicopter.

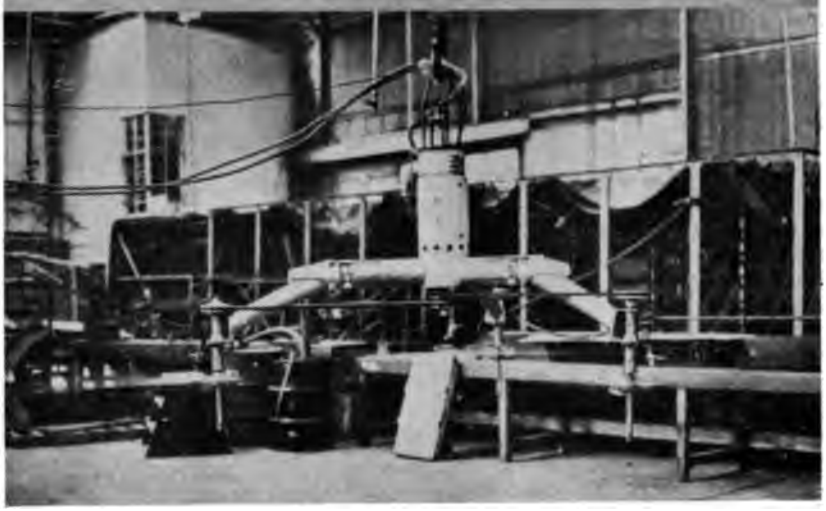
Then again we may use three rotors, the plan form geometry giving a relative spacing of the

rotors of 120 degrees. This, incidentally, becomes interesting, because it is possible to have two of the rotors turning in opposite directions and thus cancelling domestically their torque reaction, leaving one rotor, or let us say one third of the total torque, to be balanced. This can be achieved by a slight inclination of the rotor axis producing a force at right angles to the lift to balance the torque. A further possibility is to have all three rotors turning in the same sense, dealing with a resultant torque reaction by a slight tilting of the rotor axes against the direction of the torque reaction. This proposal I have adopted for the three rotor helicopter to be known as the 'Air Horse' and now under construction by the Cierva Autogiro Co. Ltd. With this arrangement there are, of course, a number of apparent advantages, the chief perhaps being the constructional gain arising from the interchangeability of rotor blades, rotor hub components, etc. This is quite an important feature when considering service and maintenance, apart from reduced cost of production, especially where jigs, tools and moulds, as for the rotor blades, are involved. There is also an indication that, purely from the stability angle, the three rotors, turning in the same sense, gives the optimum arrangement.

Powered model tests now in hand are confirming such contentions.

Before turning to the single rotor machine, I would like to emphasise an important point, although it is purely a secondary effect. When the axis of a rotor is inclined from the vertical, we get a resultant torque reaction about the rotor axis. As a simple explanation, we might take the case of a normal fixed wing aircraft fitted with an airscrew in the nose of the machine.

When the airscrew is running there is a torque reaction in the opposite sense around the longitudinal axis of the machine. This tends to lift one wing and depress the other, a feature well known to aircraft designers and pilots. If we now turn the axis of the engine crankshaft through 90 degrees so that the airscrew is above the fuselage, we have, of course, an arrangement similar to that of the helicopter. The torque reaction is now present in the fuselage about the yawing axis. Let us now choose a position for our engine crankshaft axis 45 degrees from the horizontal. The torque reaction is consequently divided between the yawing and rolling axes. From this it will be understood that if we take a normal helicopter and incline our rotor axis in a forward direction, also assuming the rotor is turning in an anti-clockwise direction looked at from underneath, there will be a residual torque reaction tending to roll the machine to port. On the other hand, should the rotor axis be tilted to port, then the residual torque reaction will tend to raise the nose of the aircraft. This is a very important effect and introduces many practical difficulties in stability and control. I have mentioned this phenomena as some designs have been proposed and are in the course of being built with the rotor axes set in inclined positions. The secondaries arising from such an arrangement must be given every consideration. No doubt you are aware of the close meshed side-by-side rotor arrangement, originally proposed by the Cierva Autogiro Co., Ltd., and subsequently made by Flettner in Germany and Kellett in the U.S.A. In this case, even the small included angle between the rotor axes introduces difficulties with control and stability.



7. Three rotor wind tunnel model powered by 28 h.p. electric motor as tested at R.A.E., Farnborough.

8. The same model inverted as run in the tunnel.

In the single rotor class helicopter, I will at first refer to the type put into practical operation by Igor Sikorsky. I should like to pay tribute to Sikorsky's work, mainly in connection with the practical application of the helicopter and the tail rotor system of torque balance in particular. It was, of course, proposed many years ago and decried by some engineers who suggested that it was impossible to balance a moment by a couple. This, of course, is true, but is not the end of the story. Placing a small rotor some distance from the main rotor axis, i.e. at the tail end of the fuselage, does not in itself balance the torque as we are left with a force in a lateral sense, which in turn must be balanced by tilting the rotor axis so as to introduce an equal force in an opposite direction. When this is done and assuming the aircraft is airborne, it may be said that the machine is now constrained in aerodynamic equilibrium. Any change in the value of the constraining influences, such as those arising from an alteration of mass trim of the aircraft or by wind differentials, necessitates a re-adjustment of the balancing forces or in other words, application of control. With the time at my disposal I shall not be able to adequately deal with other possible methods of torque balance of the single rotor machine which are of sufficient importance to warrant comprehensive treatise, but I will mention some of the work of the Cierva Autogiro Co. Ltd., that has been carried through under my direction in recent years. I will refer to:

(1) The paddle wheel type of tail rotor, which when fitted with cyclic and collective pitch can give a directed thrust reaction for the purpose of control about the yawing and pitching axes. For reference I quote the Voith System of Propulsion.
(2) Torque balance by means of two tail rotors having their axes inclined in an appropriate manner to give a similar effect to the paddle wheel.
(3) A tail rotor capable of having its axis turned through 220 degrees in the plane of azimuth.
(4) A tail rotor with a fixed inclination of its axis in some specified direction to eliminate some of the difficulties associated with forward speed of the aircraft.

As my time is limited, I will conclude the subject of torque balance by referring to the Cierva Company's research helicopter W.9.

Here torque balance is achieved by reactive thrust from a jet located at the tail end of the fuselage. During the last two years practical tests may be considered as very satisfactory.

Torque balance and yawing control is adequate and the system particularly smooth throughout the speed range. Service and maintenance has been cut to a negligible amount also a reduction of constructional weight is gained.

Ground handling is of course greatly improved and the ability to make the approved form of Autogiro landing is particularly useful. Rapid deceleration when flying as a helicopter near the ground is also possible as there is no tail rotor to protect and the aircraft can be landed tail wheel first or in the case of a nose wheel the tail skid or bumper may be used.

An additional and very important advantage is the accommodation of longitudinal shift of the c.g. by means of the tail jet deflectors. Control of the deflectors produces a

10. *Cierva W.9 as tested in October 1944.*

11. *Cierva W.9 in flight at Henley* 1945.

9. *Cierva W.9 as tested in October* 1944.

16. *Cierva W.9 centre section showing enclosed engine installation.*

12. Cierva W.9 in flight at Southampton Airport.

13. Cierva W.9 in flight at Radlett S.B.A.C. display. (Note tail fin).

component force to raise or depress the tail of the machine at will. This, in conjunction with an *appropriate* system of rotor control, eliminates the necessity of flying the aircraft on attitude, i.e. the fuselage can remain on an even keel during acceleration from hovering, when decelerating or during forward speed.

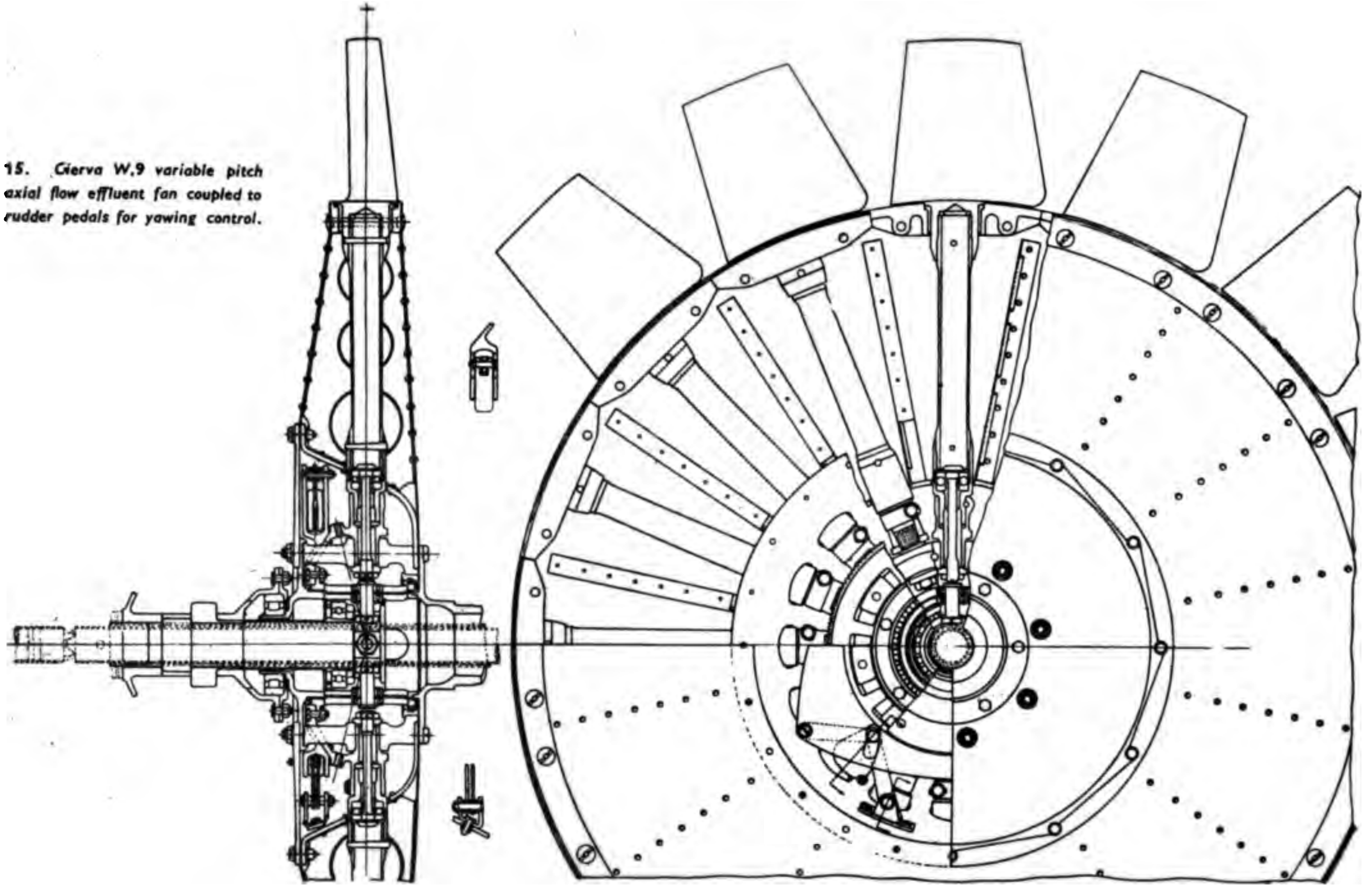
14. *Cierva W.9 Gipsy engine unit (200 h.p.).*

This jet system, when subjected to the merciless guillotine of the mathematician, appears very uneconomical, but proper evaluation can only be established when all the accompanying advantages are placed in the scale pan. Owing to the relatively high velocity of the effluent, about 150 ft./sec. the loss of kinetic energy is greatly in excess of that of the low velocity slip stream of the small tail rotor. To balance this, the heat dissipated by the engine cylinders and exhaust gasses is utilised, admittedly at low thermal efficiency, to increase the reactive thrust, with a consequent reduction of the fan h.p. As some 65 per cent. of our fuel energy is wasted in the cooling system and exhaust gasses, we can, even at low efficiency, regain some useful horse power or its equivalent. In the case of W.9, when hovering, this amounts to approximately 9 h.p. the heat, of course, increasing the velocity of the effluent at the jet.

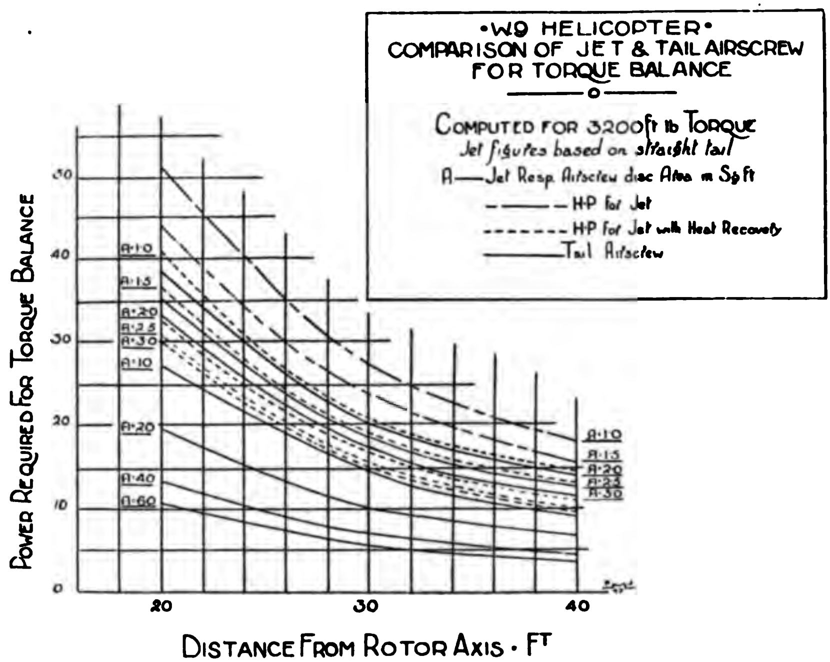
It is important to understand that the heat is added after compression of air by the effluent fan, which operates in this case at pressure datum of approximately .35 lbs. above atmospheric pressure.

Assuming the appropriate tail rotor was fitted to this machine, in hovering the jet system would require an additional 2.5 h.p., which translated into terms of lift on the machine in question, at say one rotor diameter from the ground, would represent some 42½ lbs. This, incidentally, would be more than saved in constructional weight. At cruising speed the effluent fan, having variable pitch blades, is feathered so that the aerodynamic rudder and directional properties of the fuselage are in action, the resultant drag being equivalent to approximately 2.3 per cent. of the h.p. required for the cruising condition.

It may be appropriate to introduce at this juncture, the advantages and disadvantages of gearing the tail rotor to the main rotor. It is admitted that in an emergency vertical descent the tail rotor gives control about the yawing axis, which is most important if the machine is to be positioned correctly especially if drift is present prior to landing. On the other hand, the tail rotor is equivalent to a brake on the main rotor and is to some extent responsible for the high rate of vertical descent of some of the helicopter aircraft now in use. It may be argued that the tail rotor blades when set at zero pitch will not take any appreciable power from the main rotor. Even the windage of the feathered tail rotor produces a torque reaction about the rotor axis so that some pitch is required to effect balance about the yawing axis. A figure of 3.5 h.p. has been calculated for a given machine and



15. Cierva W.9 variable pitch axial flow effluent fan coupled to rudder pedals for yawing control.



the equivalent braking torque is thus applied to the sensitive autorotating rotor. I have neglected the gliding case with the tail rotor positioned for autorotative effect.

In the case of W.9, the free wheel is in the rotor hub so that the effluent fan becomes inoperative during an emergency landing under autorotative conditions. Intentional autorotation can be enjoyed as the pitch range of the fan blades permit even a slight reversal of the flow at the jet orifice. In pure vertical descent, as say from 80 feet, the aerodynamic rudder of W.9 would be substantially inoperative. The aircraft is consequently fitted with a final positioning device in the form of two fluid jets connected with a small accumulator, charged to a pressure of 3000 lbs/sq. in. The jets are brought into action by an emergency button but under the control of the normal rudder pedals. A supply of one gallon of fluid is sufficient for the requirements and lasting some 10 seconds and at a rate of vertical descent of say 40 ft./sec., we have sufficient yawing control as from 400 feet above the ground. The total weight of the apparatus is less than 20 lbs. On this particular machine the hydraulic components, including the fluid, are already available as part of the servo rotor control system.

In spite of the shortness of time at my disposal, I feel I should say a few words regarding torque balance by means of aerodynamic surfaces located in the slip stream of the rotor. The calculations as to the amount of surface required are comparatively easy when the slip stream velocity is known. On the score of efficiency this velocity will be of a relatively low order, and in

the experiments I have in mind was within the region of 40 ft./sec. The location of the aerodynamic surfaces in relation to the rotor is not so easy, it being very difficult to establish the axial distance from the plane of the rotor where the slip stream is fully developed. I understand that full scale tests had been conducted by Haffner, Focké, Platt and others, but I was determined to carry out a theoretical and practical investigation, the latter in model form, to ascertain as to whether the method represented a possible solution.

17. Wind tunnel model of torque balance project having adjustable surfaces located in rotor slip stream.

The model constructed for test is that shown on the screen, but was first designed to have only one surface which should have been ample for the purpose, the duplication being added subsequently. For the purpose of convenience, the actual rotor with articulated blades was mounted on the driving shaft of an electric motor, the fuselage being suspended underneath on anti-friction bearings to permit freedom about the yawing axis. A single horizontal hinge allowed the model to turn about the pitching axis, the whole being supported in the wind tunnel. Moments about the yawing and pitching axis could be taken whilst under the influence of the rotor slip stream. Sufficient freedom was also available to allow the model of the fuselage to rotate through 360 degrees in azimuth. The floor of the tunnel was adjustable from two rotor diameters from the plane of the rotor to within a quarter of the rotor diameter. To describe the full details of the test is beyond the scope of this meeting, but I am sorry to say the results were most disappointing. Briefly, it appeared that when the complete model was free to enjoy full symetrical rotor circulation, the aerodynamic surfaces could be adjusted to balance the torque reaction, the torque moment of the model being checked against the torque reaction of the motor casing. As soon as the adjustable floor was brought within one rotor diameter of the plane of the rotor, strange things began to happen, the torque reaction became unbalanced and on one occasion was over determined. Even a rectangular hole in the wall of the tunnel some 15 in. square, to accommodate the balance arm of the model, would, when the fuselage was free to spin, create an effect sufficient to momentarily arrest the model for 1 to 2 seconds. As a point of interest, the area of the aerodynamic surfaces in relation to the disc area was, in the case of the single surface, some 7.15% and when duplicated 14.3%. I am not suggesting that it is impossible to eventually reach a solution by this approach, although I am very doubtful whether precision flying near the ground would be possible. The German Dublhoff helicopter with jet reaction from the blade tips and employing aerodynamic surfaces for yawing control only, was shown on the screen during Captain Liptrot's lecture. The erratic displacement of the aircraft when a few feet from the ground confirmed in full scale, the tests I conducted in the wind tunnel. I understand that Dublhoff's latest helicopter has discarded the aerodynamic surfaces for a tail rotor driven from the main rotor,

purely for the purpose of adequate control about the yawing axis during hovering and when in slow translational flight.

To conclude this brief resumé of torque balance, it now appears, that if we completely eliminate torque reaction in the body of the aircraft, we have lost control about the yawing axis when hovering or flying close to the ground. It thus becomes necessary to provide mechanical means for yawing control, as for instance, in the form of a small tail rotor or fan. A further important point is the effect on stability and control, which will be dealt with later.

Rotor Blade Mounting

This may be divided as follows:—

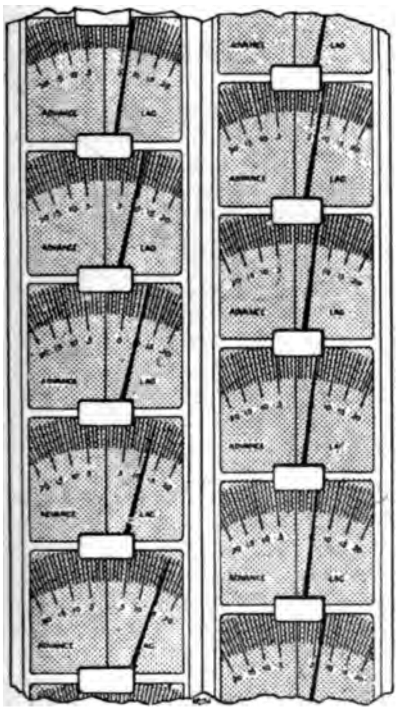
1. Non articulated rotor blades, commonly called the rigid rotor, which of course is a misnomer.
2. Fully articulated rotor blades.

We find many combinations in use to-day and from my experience I am in favour of the fully articulated rotor blade system. In connection with this, it must be understood that the rotor blade or blades must be *fully articulated* under all airborne conditions. The only time that one degree of freedom may be lost is during the initial stage of starting the rotor, when of course, the blades will lag on to the back stops. There is a definite reason for this requirement of free articulation and although it may be said the helicopter is incapable of being stalled in the same manner as a fixed wing aircraft, nevertheless, it is possible to stall the rotor under certain conditions of helicopter and Autogiro flight. This would mainly be attributed to an error of pilotage or lack of appreciation of the necessary blade pitch or angle of incidence to deal with intentional or emergency cases. I wish particularly, to refer to individual blade stalling brought about by a concatenation of circumstances, which would normally cause a blade or blades to stall. With the freely articulated blade this can be avoided by the upward flapping movement giving a virtual reduction of blade incidence and thanks to its curvilinear path is soon out of immediate danger. This, I believe, is termed by our American friends as "sailing" of the rotor blade. The required freedom is quite considerable and a lack of appreciation of this requirement was responsible for the loss of the rotor blades on my early experiments with helicopters W.5 and W.6. In both instances drag and flapping freedom was approximately half of that necessary to meet the conditions. In the case of a three bladed rotor, if one blade becomes stalled the inertia torque of the other two blades is of such magnitude as to cause the stalling blade to break, either at the root end or approximately at half the blade radius, unless it is free to "sail" about its articulated restraint. I have recent evidence of helicopter blades that have been forced against the top flapping stops indicating a vertical flapping displacement of the blade or blades of over 37° from the horizontal. Knowing all the relevant parameters and taking the coning angle as 6° it is possible to evaluate the kinematics and the resultant portent.

With such large orders of flapping displacement an examination of the control mechanism is advisable. If we take the usual blade control arm mounted near the root end of the blade and assuming the upward flapping displacement was 90°, then the swash plate control mechanism becomes inoperative. Even at 37° displacement the effect becomes apparent. It is for this reason that

I favour the internal blade control mechanism of the Weir helicopter W.6.

In the case of the non articulated rotor blade, we find, that should conditions arise to promote an incipient stall, then the blade is unable to " sail " so as to virtually reduce its incidence. The incipient stage is followed by the full stall on account of the inertia torque of the remaining blade or blades. To make



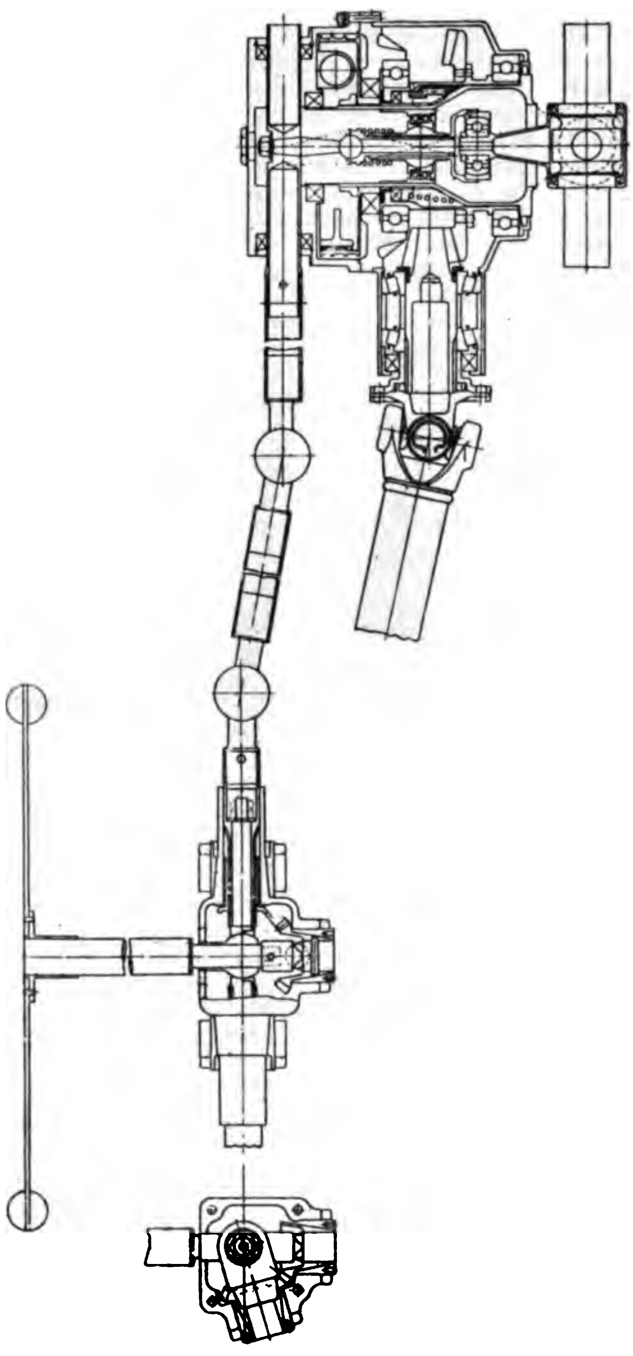
19. *Film cut of rotor blade displacement to check blade kinematics.*

the blades sufficiently robust at the root end becomes uneconomical, and even so, the point of fracture will be moved along the blade towards the tip but is likely to occur at about .6 of the blade radius. If we endeavour to increase the strength of the blade at this point we run into difficulties from the aerodynamic aspect.

The use of non articulated blades attached to an unarticulated rotor hub is, of course, only permissible on multi-rotor machines when the rotors can be arranged to turn in the opposite sense to domestically cancel out the gyroscopic moments. Vertical bending loads also bending in the plane of azimuth can be reduced by buliding-in of the mean coning and drag angles. On the other hand, a modified arrangement of non articulated rotor blades is that wherein the blades are secured to an orientable hub or gimbal component. This eliminates the gyroscopic moments from the machine but differential blade flapping is prohibited. In turn we get disc flapping or tilting of the rotor disc which can be under control of a swash plate or cyclic pitch, or by cross pin constraint as is the case of the orientable hub. Unfortunately, either arrangement does not permit of blade " sailing " and in my opinion is undesirable. In talking of articulated and non articulated rotor blades I am excluding the torsional pitch change hinge which performs the separate functions of cyclic and collective pitch.

I have found that some rotor systems will behave perfectly for many hours of hovering and normal flight until a particular set of circumstances arise which are beyond the capabilities of the system. Such circumstances may be due to one of or any combination of the following:—

1. Gust effect causing a considerable displacement of the aircraft about the rolling, pitching and yawing axes or inter-related effect.
2. Change of angle of attack of the relative wind by as much as 90°.



20. Weir W.5 rotor hub and control organs.

3. Mis-application of control in correcting numbers 2 or 3.

4. Dissymetrical rotor circulation.

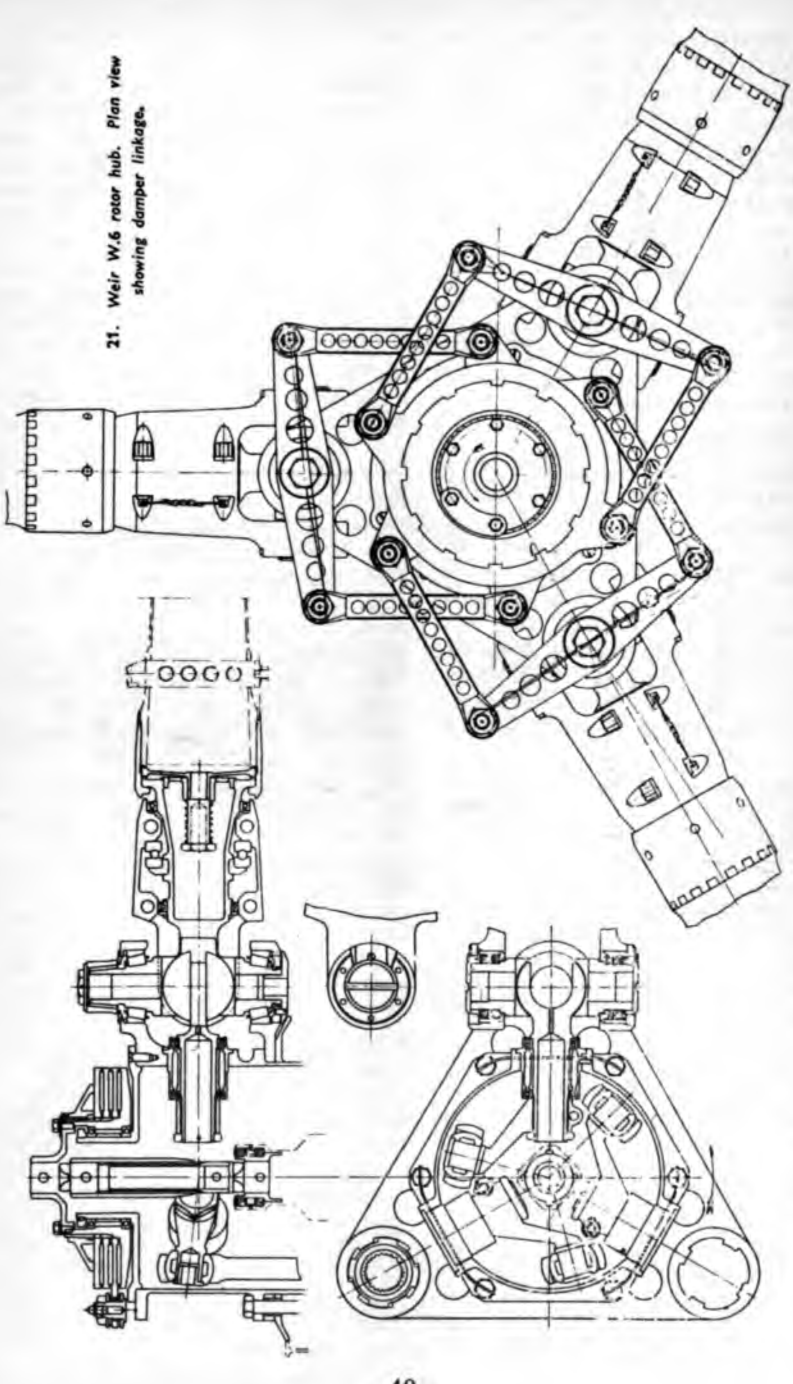
Although the foregoing remarks mainly apply to the helicopter, it is also possible, under certain circumstances, to run into trouble by overdoing a flared-out landing under conditions of autorotation. This was not the case with the old Autogiro as the control range was strictly limited and the drag and flapping stop clearance commensurate with the requirements but at the cost of limited control range.

Rotor Systems

During the last 14 years I have been responsible for, and associated with, many designs of full scale rotor systems also a large number of working wind tunnel models. As a matter of fact, it would be difficult to suggest an arrangement that has not been fully investigated both on paper and in some practical form or another. My early work was confined to the orientable direct control Autogiro rotor systems which also included the jump start Autogiros, which were, of course, helicopters during the period of direct take-off. The many years' experience with the orientable rotor hub brought to light the advantages and also the limitations of this system, the latter being of such magnitude that I considered the most appropriate method for the control of the helicopter was that of cyclic pitch. This system was adopted for Britain's first successful helicopter, the Weir W.5.

Cyclic pitch was also used on its successor, the Weir W.6, but I reverted to the orientable rotor hub for the Cierva helicopter W.9. Some explanation is perhaps necessary.

It has been shown by Locke, Wheatley and others, that cyclic change of the blade pitch is equivalent to sinusoidal flapping for the purpose of equalising the lift round the disc, as is necessary in forward flight or when hovering in gusty weather. Whilst this is true, we find a marked difference in the two systems. Let us assume that our aircraft is hovering in still air and we incline our control column to effect forward translation. In the case of the orientable hub, we tilt the tip path plane of the rotor or let us say disc, and the resultant translational force commences to accelerate the machine. During the initial period of acceleration the rotor remains in symmetry and is consequently smooth or vibrationless. As our forward speed increases, the differential flow will in turn produce differential flapping of the rotor blades and the aircraft will become progressively rougher in relation to the translational speed. The lift vector of the rotor will now be tilted back, the machine tending to climb unless the control column is pushed forward, so that the limit of forward control range is quickly reached. To deal with this unhappy state, it is necessary to employ means to suppress the flapping or alternatively tilt the rotor forward by changing the attitude of the fuselage, thereby regaining some of the forward control range. Now with the cyclic pitch control system, when the control column is moved forward to accelerate as from the hovering condition, we immediately introduce differential flapping and the aircraft becomes quite rough. This roughness will persist if we attempt to keep the fuselage on say an even keel, so that to enjoy reasonably smooth translational flight the rotor disc must be tilted, which, of course, is directly associated with the attitude of the fuselage. By the correct co-ordination of throttle, aircraft attitude, and application of cyclic pitch, we can reach an optimum speed at which the aircraft remains reasonably smooth.



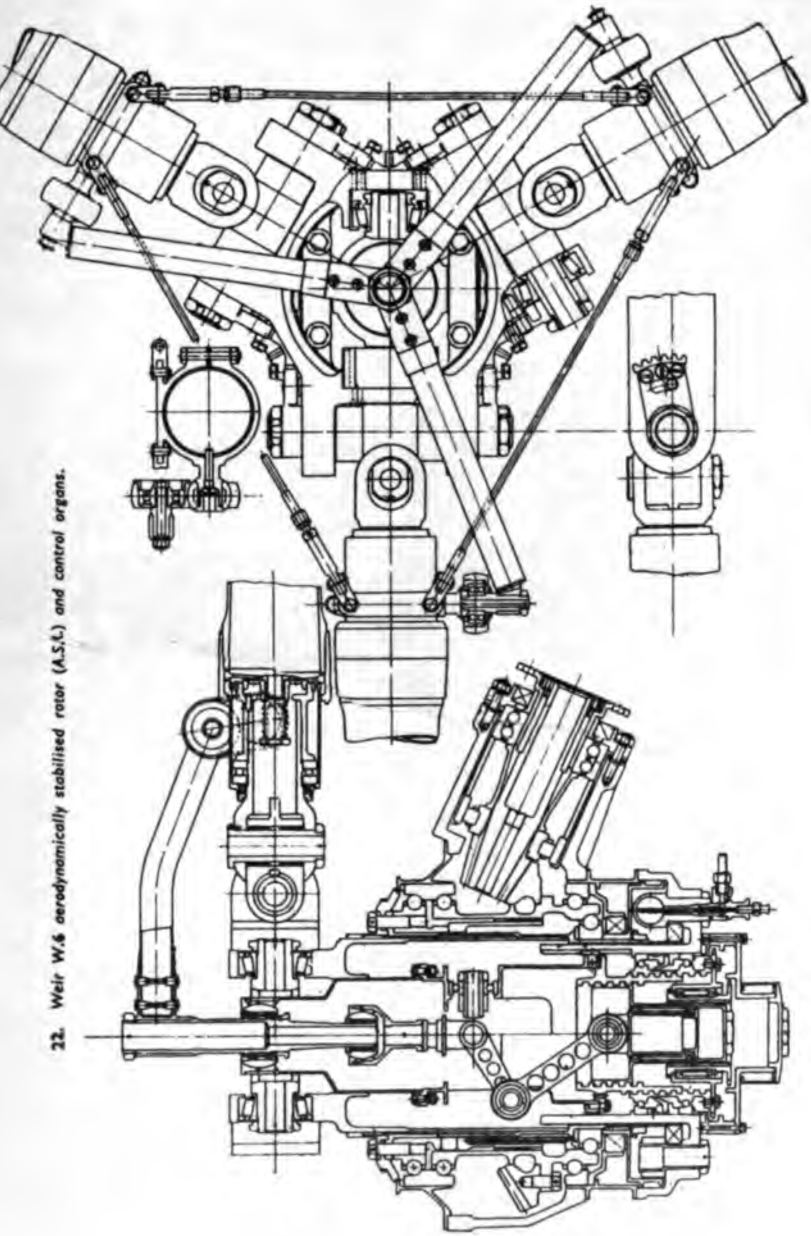
21. Weir W.6 rotor hub. Plan view showing damper linkage.

It is thus obvious that one of the difficulties with the orientable hub is that of the suppression of flapping. A Delta III effect or pitch change coupled with flapping displacement was embodied in a rotor system termed the A.S.R. and tested in full-scale on helicopter W.6.

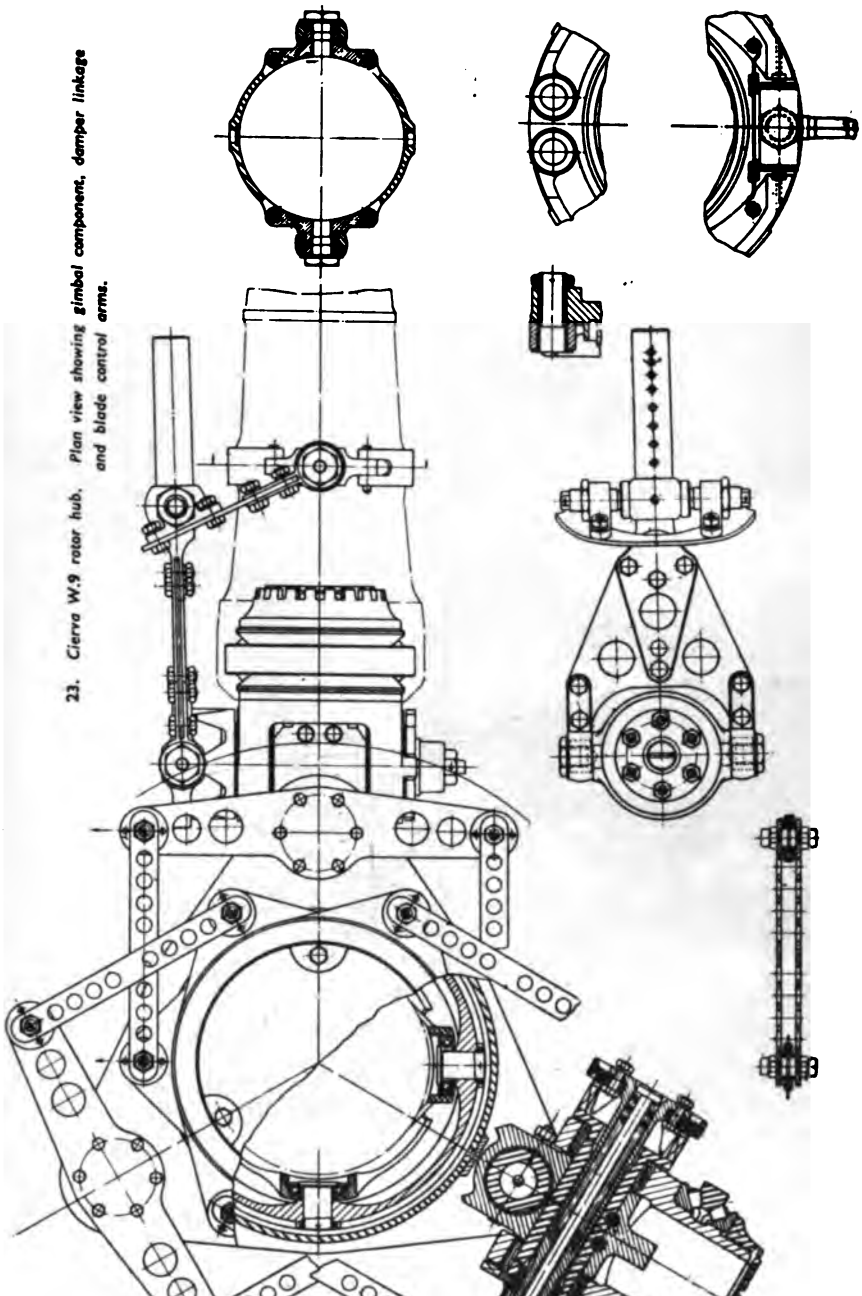
The results were very promising but the experiments were curtailed owing to the turn of the war in July, 1940. In this system, the three rotor blades were attached to a hub which in turn was mounted on a gimbal component. The rotor blades were provided with drag and flapping hinges but bridled in such a manner as to permit of coning of the three blades but suppressing the differential flapping. Arms from the blade torsion hinges were under control of a swash plate mechanism so that the rotor disc always followed the inclination of the swash plate. It will be understood that as differential flapping was suppressed, the rotor as a whole was constrained to flap or tilt about the gimbal component. Gust effect or differential flow would cause the disc to tilt about the gimbal component whereas the swash plate datum remained fixed. This in effect reduced the blade pitch in a cyclic manner and was substantially equivalent to a control effect on the part of the pilot. Unfortunately the rotor or disc tilt of this system has a precessional characteristic and whilst this is cancelled out domestically on a multi-rotor machine, I do not recommend its application to single rotor machines.

As my experiments with cyclic pitch control were substantially completed in 1940, it was agreed that no immediate useful purpose would be gained by making, at that juncture, some practical examples for operational duties but an endeavour should be made to develop the A.S.R. system which, in spite of certain limitations, had displayed practical advantages. An elegant solution appeared possible with the orientable hub arranged with a large order of Delta III. Wind tunnel model tests of this project indicated the possibility of a self incidence setting rotor close to the optimum of that suitable to helicopter operation together with an automatic changeover to the optimum setting for autorotation. A full-scale rotor was not completed until 1944, and when tested, immediate difficulties were experienced with the control.

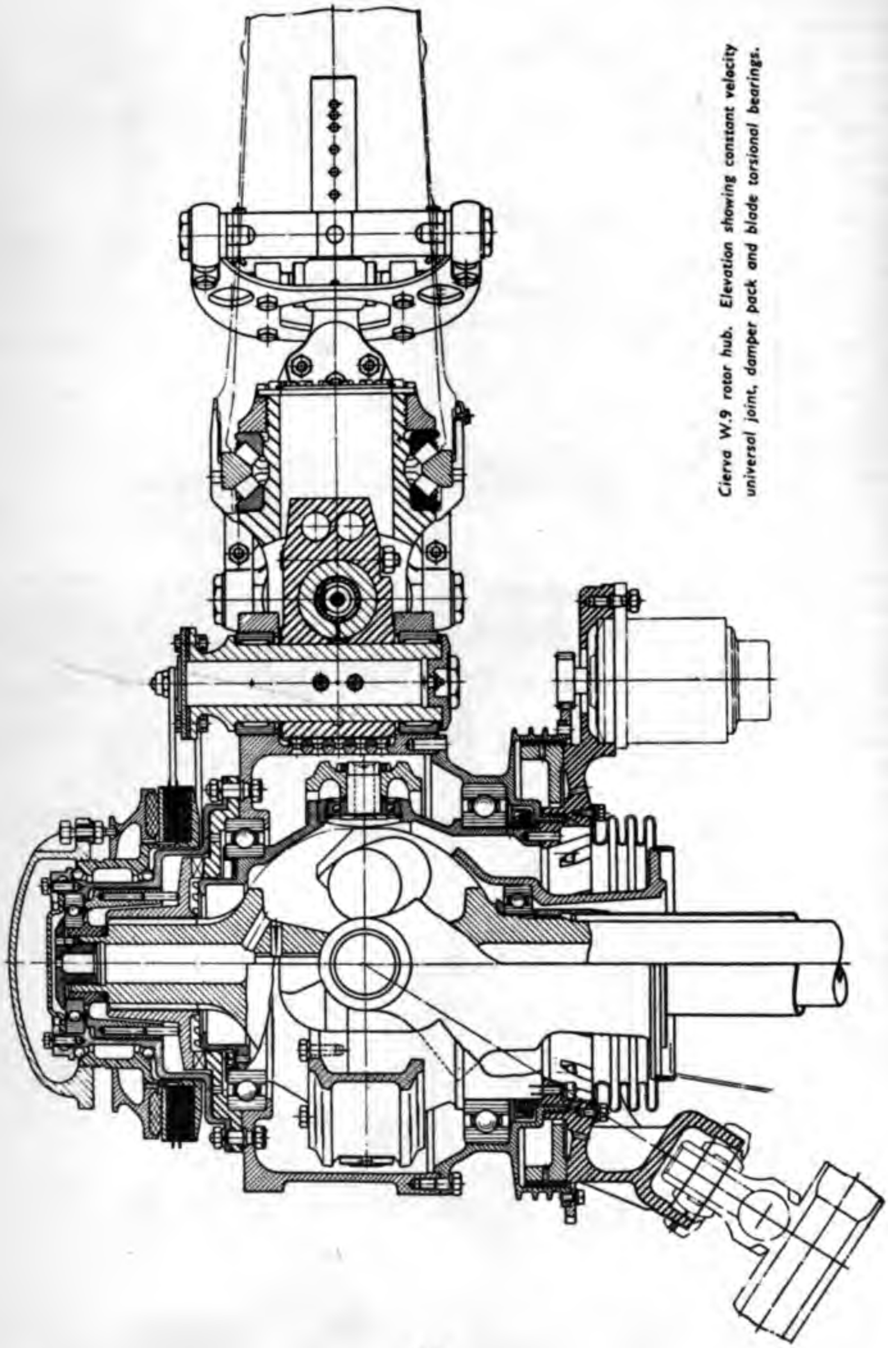
A careful investigation traced the trouble to control phase and although the machine was hovered for a considerable number of hours, full control was not gained until the Delta III had been back coupled as from one blade to the other to thus correct the phase and in accordance with the value of the Delta III in use. To clarify this, the flapping displacement of one blade would change the incidence of the following blade and so on with the other blades. This system has proved quite successful in test and is very smooth throughout the speed range. On the other hand, it has been necessary to speed up the rate of control application by means of a hydraulic servo mechanism to give the instantaneous response necessary to check the displacement of the aircraft. The range of angular tilt of the hub is also excessive. Although the system may be considered as adequate to meet all the requirements of normal flying, it falls short of certain essential qualities for precision flying close to the ground. This is mainly due to the fact that the rotor spills off any excess lift, the lift being in accordance with the value of omega or let us say rotor r.p.m. With unlimited power at our disposal we could get sufficient acceleration of the rotor to deal with the rapid



22. Weir W.6 aerodynamically stabilised rotor (A.S.L.) and control organs.



23. Cierva W.9 rotor hub. Plan view showing gimbal component, damper linkage and blade control arms.



Cierva W.9 rotor hub. Elevation showing constant velocity universal joint, damper pack and blade torsional bearings.

alteration or variations of height when close to the ground but in practice, as the reserve power is somewhat limited, it seems expedient to take advantage of the kinetic energy stored in the rotor. By the use of collective pitch it is possible to use the stored energy to meet the exacting requirements of the case mentioned.

Having thoroughly explored both the cyclic and collective pitch control systems also the plain orientable hub and in conjunction with Delta III effect, I am now able to propose a combination arrangement escaping the limitations of both systems but retaining the good features of each. Unfortunately, it is not possible, at this juncture, to release any relevant information but it is hoped that the wind tunnel model now on test will be represented in full-scale on the Cierva W.9 research machine by the end of the year or shortly afterwards.

It will be appreciated that I could take up a great deal of time in describing my work with various rotor systems, so in the circumstances I must now turn to the next item, i.e., Rotor Blades.

25. Cierva W.9 wind tunnel model of new Delta III rotor hub.

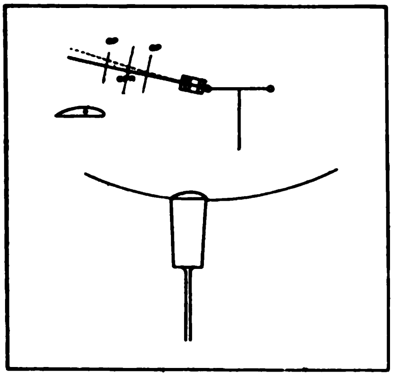
26. Cierva W.9 model hub mounted in the wind tunnel.

27. Cierva W.9 Delta III hub on test in the wind tunnel.

Rotor Blades.

Under this heading, we have perhaps the most important component of the helicopter aircraft, involving the usual conflict of aerodynamic requirements and constructional limitations. I should qualify this by saying that great care must be paid to the design if reasonable efficiency is to be achieved. Some helicopters that have flown and are still in use, show lift efficiences of quite a low order, being in the region of 60% as against some 82% that is possible by careful choice of the major parameters. Unfortunately, the ideal aerodynamic requirements introduce structural limitations so that the ultimate choice is that of compromise. The desired blade kinematics in forward flight and when the rotor is under the influence of the control column, as in the hovering state, are only possible if the blade construction is such as to permit the blades to react correctly to the pilot's con trol. Let us take a rotor blade mounted on its hub component through the medium of drag and flapping hinges, also a torsion hinge, so that the blade may be controlled in pitch by suitable mechanism, as for instance a swash plate under

influence of the pilot's control column. If the blade in question is very flexible in the torsional sense and unless we arrange our mass distribution in an appropriate manner, it will be found, that the application of the pilot's control to the root end of the blade will fail to be communicated to the tip end or to the region where the change of incidence is most effective. A further difficulty arises from bending of the blade in the vertical sense as by the application of control by turning the blade about the torsion hinge the outer portion, particularly the blade tip, will describe an arc, the radius of which will depend on the amount of bending.



28. Diagrammatic sketch relating to periodic bending of rotor blade.

If it is possible to reduce the bending to zero, the blade will, of course, turn about its longitudinal axis. Quite severe moments can be present in the control column unless the bending is kept to a very low order. It will also be realised that in translational flight or under gust conditions, the effect of differential flow will introduce an excursion of the centre of aerodynamic pressure in relation to the centre of percussion of the blade. Under these conditions we have a periodic bending of the outer portion of the blade corresponding to the movement of the centre of pressure in relation to the centre of percussion, so that the outer portion of the blade is subject to upward bending over one half of its path round the disc and downward bending over the other half. I will not deal with the attendant difficulties, but when associated with relatively flexible blades the application of control or gust effect may introduce some serious problems and the practical results can be disastrous. By careful design, it is possible to arrange the mass distribution together with methods of construction that will result in reducing periodic bending to a marginal figure. Reducing the flexibility to a low order will enable the pilot to control the blade kinematics to requirements. As a point of interest, I would mention that the calculated vertical bending of one set of rotor blades of W.9 under hovering conditions is .5 in. at the tip and on a second set the bending has been reduced to less than .3 in. The torsional stiffness of both sets of blades is considerably greater than in general use on most helicopters.

As a possible alternative to changing the blade incidence by mechanism attached to the root end of the blade, the aileron method offers certain advantages. As the outer third of the blade is the most effective it seems logical that the control should be imposed on that portion. It is doubtful if change over from helicopter to autorotation can be accomplished by aileron alone and if the mean setting for helicopter operation is to be efficient then the autorotative setting will be difficult to realise. This necessitates a torsion hinge for the change over so that aileron control can be restricted to within reasonable limits or just sufficient for correcting normal displacements of the aircraft. The

system when coupled to cyclic mechanism should be capable of carrying through the desired blade kinematics and I hope to fully investigate the possibilities at an early date. The idea is not new and was proposed by quite a few of the early experimenters. We also have the modern examples of Langraf, Bendix and others.

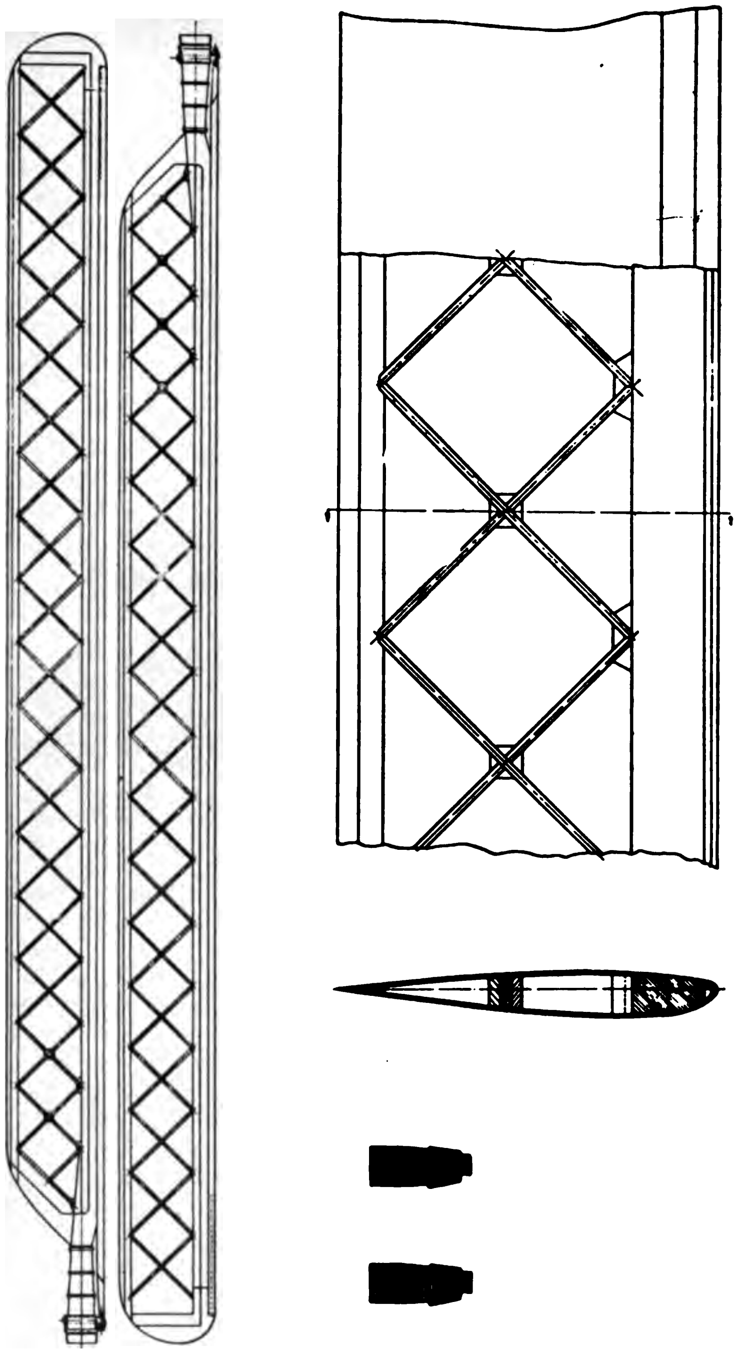
The importance of correct blade kinematics becomes predominant in translational flight at say over 60 m.p.h. as the cyclic system of control together with the attitude of the aircraft gives the necessary pitch oscillation to suppress flapping.

Inability to achieve smooth high speed flight can be attributed to a lack of appreciation of appropriate apparatus to achieve the required blade kinematics. The use of modern low drag areofoils have contributed largely to the increase of lift efficiency now being attained, but torsional stiffness is very elusive when relatively low fineness ratios are employed. On helicopters W.5 and W.6 the blades had a fineness ratio of 12% and the section in accordance with N.A.C.A. 23012. Great difficulty was experienced with the construction of these blades, cruciform type of rib being used to reduce the torsional and bending flexibility.

For W.9 I decided to sacrifice some aerodynamic efficiency by using a 15% fineness ratio and the resultant stiffness is considered to be satisfactory. I would also mention that the stalling curve of the N.A.C.A. 23015 is not so abrupt as that of the 23012 section.

In the light of past experience with Autogiros and the difficulties of obtaining blades of uniform characteristics, I decided to employ an all wooden blade construction for the Weir helicopter W.5 using moulded synthetic resin bonded plywood skins.

These early examples of semi-moulded blades were made by Messrs. Airscrews Ltd., Weybridge, and Jablo Ltd., of London. The same principle of moulded skins and compressed wood spars was used on the Weir helicopter W.6, the blades being made by Messrs. Morris & Co., Glasgow, high class woodworking engineers. I may say that this method of construction has given every satisfaction and was adopted in modified form for the rotor blades of the Cierva helicopter W.9. It is of interest to note that in the case of the Weir W.5 and W.6, the blades were of constant chord throughout and untwisted, whereas those of W.9 have a pronounced taper plan form and twisted out of incidence towards the tip by some 6°. The estimated and measured lift efficiency of the W.9 is over 80%. In the case of W.6 the transverse C.G. position of the blades was corrected by rolling-on to the leading edge of an extruded monel metal section, the inner end being anchored to the root fitting so as to relieve the wooden portion of the blade of the centrifugal load of the metal edging. The blades of the Cierva helicopter W.9, constructed by Messrs. Morris & Co., of Glasgow, have the transverse C.G. corrected by means of lead weights built into the blade spar, whereas those made by Jablo Ltd. employ embedded sintered tungston weights having a specific gravity of 16.9. The use of this heavy metal, more than twice the weight of steel, simplifies the problem of accommodation in the spar. Apart from correcting the transverse C.G. the longitudinal location of the weights is so arranged as to reduce the vertical bending under dynamic conditions to the very small order as previously mentioned.

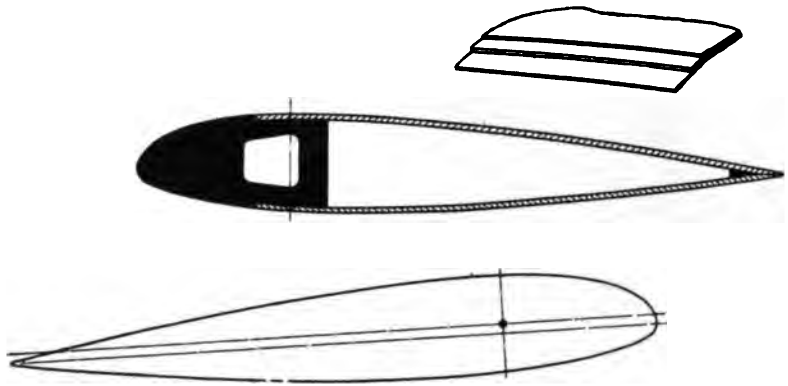


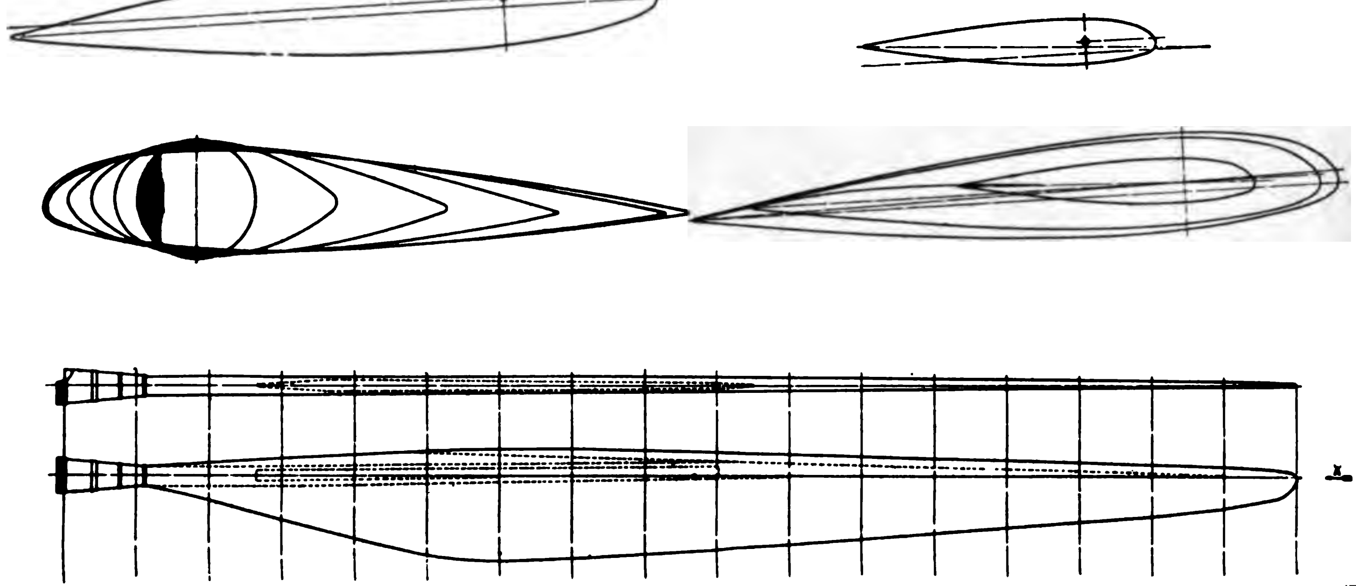
29. Weir W.6 rotor blade construction.

30. *Weir W.6 rotor blade. Stages of construction.*

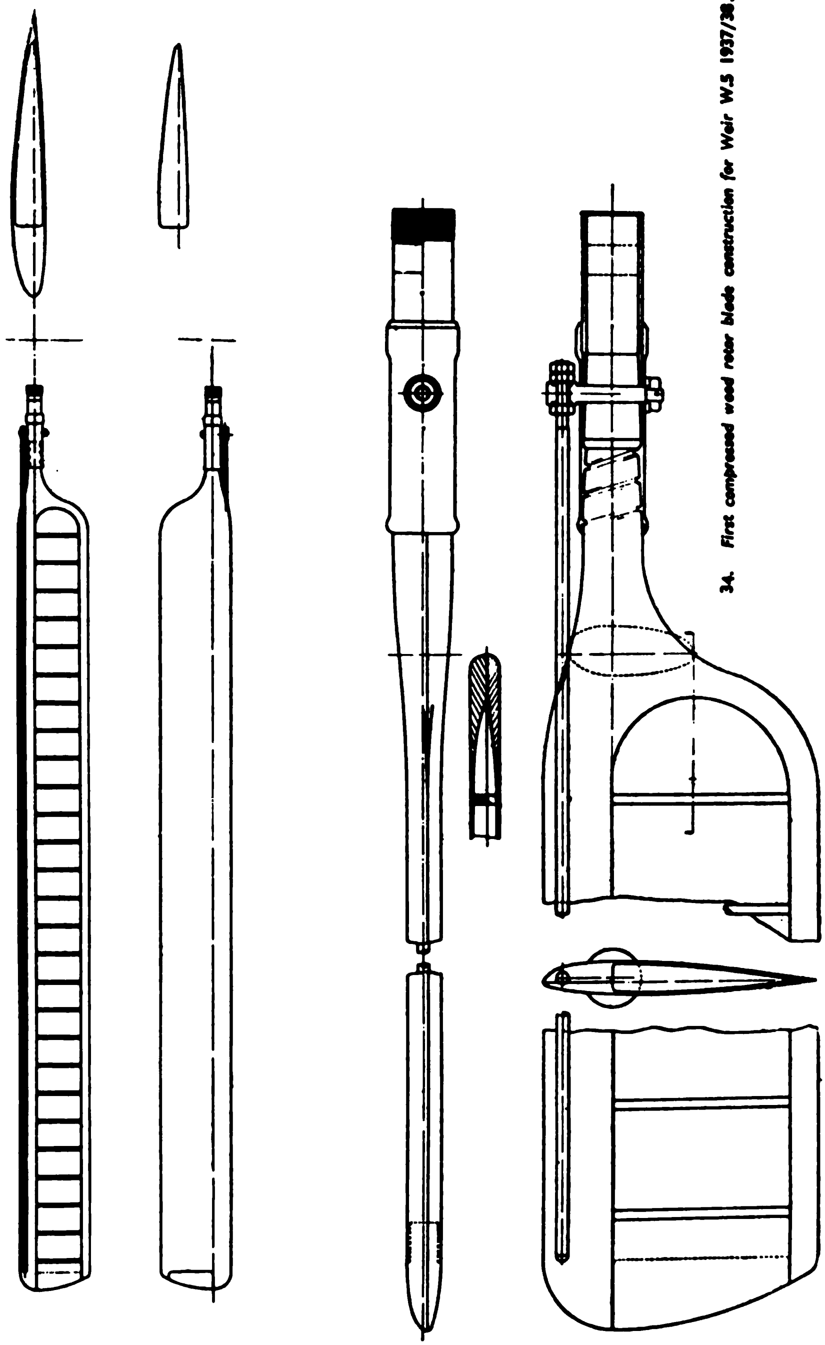
31. *Weir W.6 rotor blade supporting two men.*

32. *Root fitting of Weir W.6 rotor blade. Note metal leading edge anchored to root fitting.*

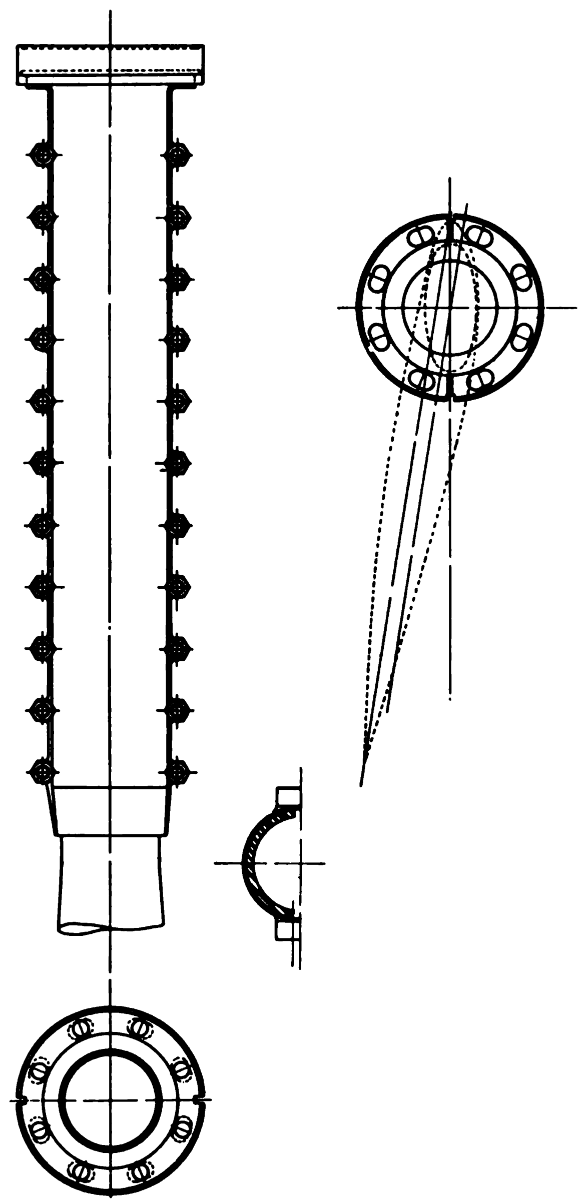


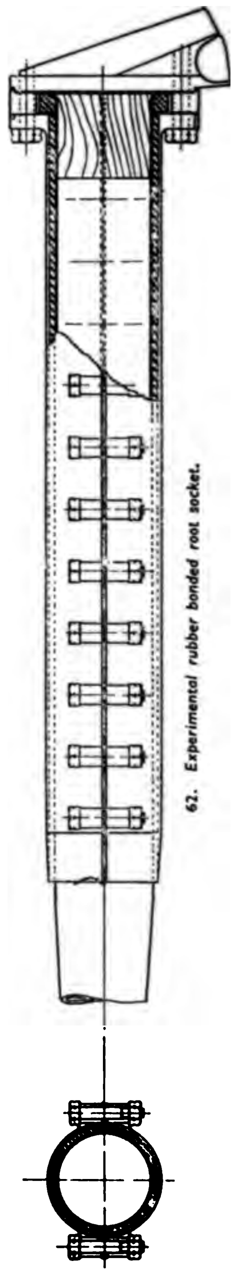


33. Cierva W.9 rotor blade. Note box section compressed wood spar and absence of transverse ribs.



34. First compressed wood rotor blade construction for Weir W.5 1937/38.



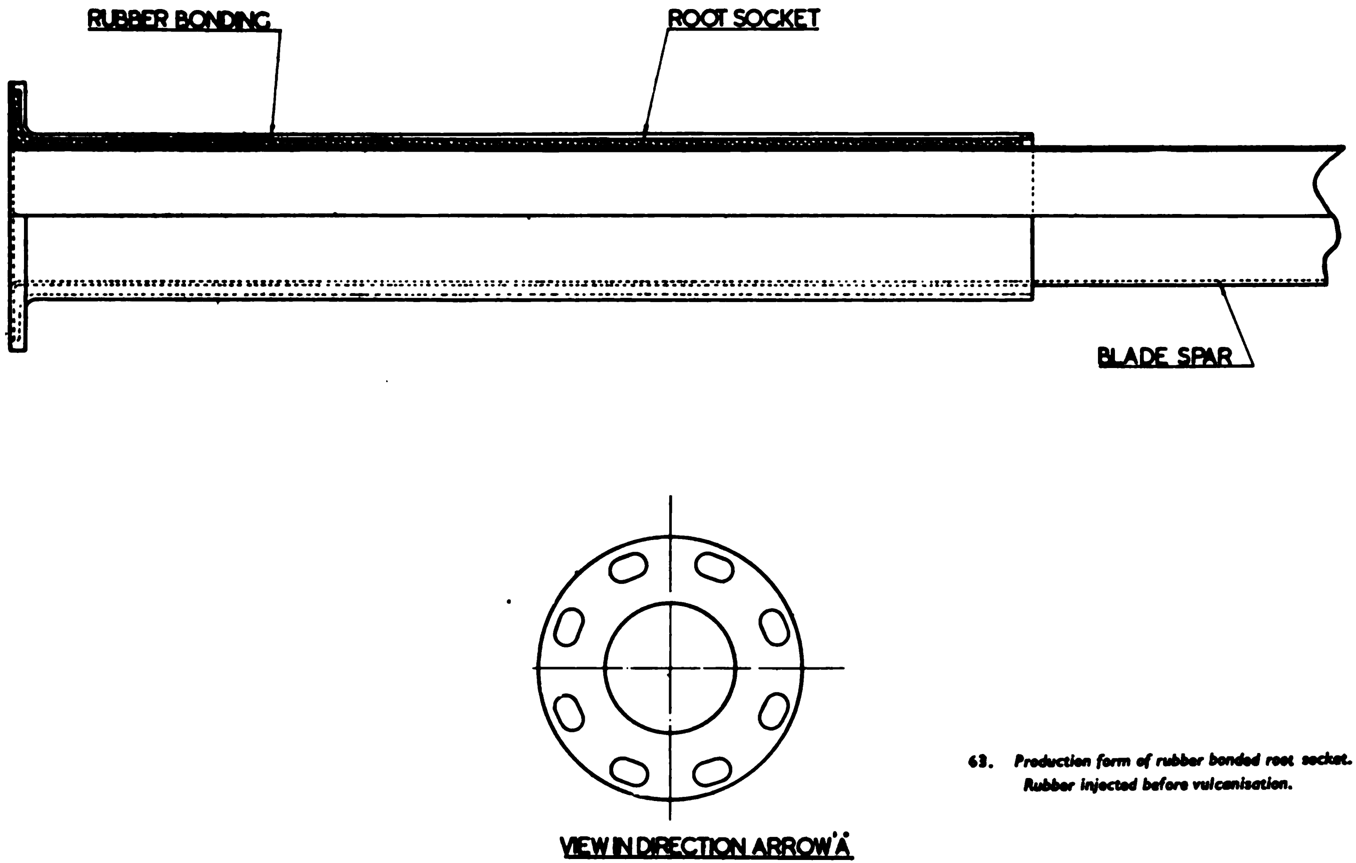


62. Experimental rubber bonded root socket.

ONE OF THE TEST RESULTS OF THE EXPERIMENTAL FITTING

Load Tons	Deflection (Elastic) Inches	Deflection (Permanent) Inches
·1	0	0
·5	0×	0
1·0	1/64—	0
1·34	1/64	0
1·5	1/64×	0
2·0	1/32	0
2·5	1/32×	0
3·0	3/64	0
3·5	3/64—	0
4·0	1/16	0
Load held at 4 tons for 3 minutes.	No further elastic deflection.	No permanent deflection.
5·0	5/64	0
7·0	3/32	0×
9·0	9/64	1/64
9·5	Tube started to fail in bearing	

NOTE. Tube was held by one No. 10 morse taper pin which in this instance had been very badly fitted causing excessive local bearing pressure on tube.



63. *Production form of rubber bonded root socket. Rubber injected before vulcanisation.*

The root fitting of the rotor blade has always been a problem in itself. When using a steel tubular spar I have found the best method to employ is that of rubber bonding the root end socket to the tube. Strangely enough the experimental fitting is still in existence as it has defied all attempts to pull the tube from its socket, mainly because no other form of root end attachment can be found with equal resistance to that of the rubber bonded end. Although this form of attachment is not in use at the present juncture, there is reason to believe that its unique properties will be fully appreciated in due course.

The form of root fitting that was used on the Weir W.6 was again employed on the Cierva W.9. A set of blades has also been tested with screwed-on root fittings similar to those of wooden airscrew blades. Both types appear to be satisfactory.

On the question of rotor blade finish, doping and polishing fails to withstand the effects of rain, hail, etc., so I arranged for one set of blades of the Cierva W.9 to be finished with Plastoglaze. This material is sprayed on and cured by means of hot carbon dioxide gas produced in a special generator. The curing process takes about 10-15 minutes for each coat, the blade being subsequently rubbed down and polished. Five or six coats at least are advised. I would also mention that static and dynamic balancing is corrected during spraying and polishing. The resultant finish is almost glass hard, impervious to water, oil, petrol, etc., and retains sufficient flexibility to prevent cracking of the coating under deflection.

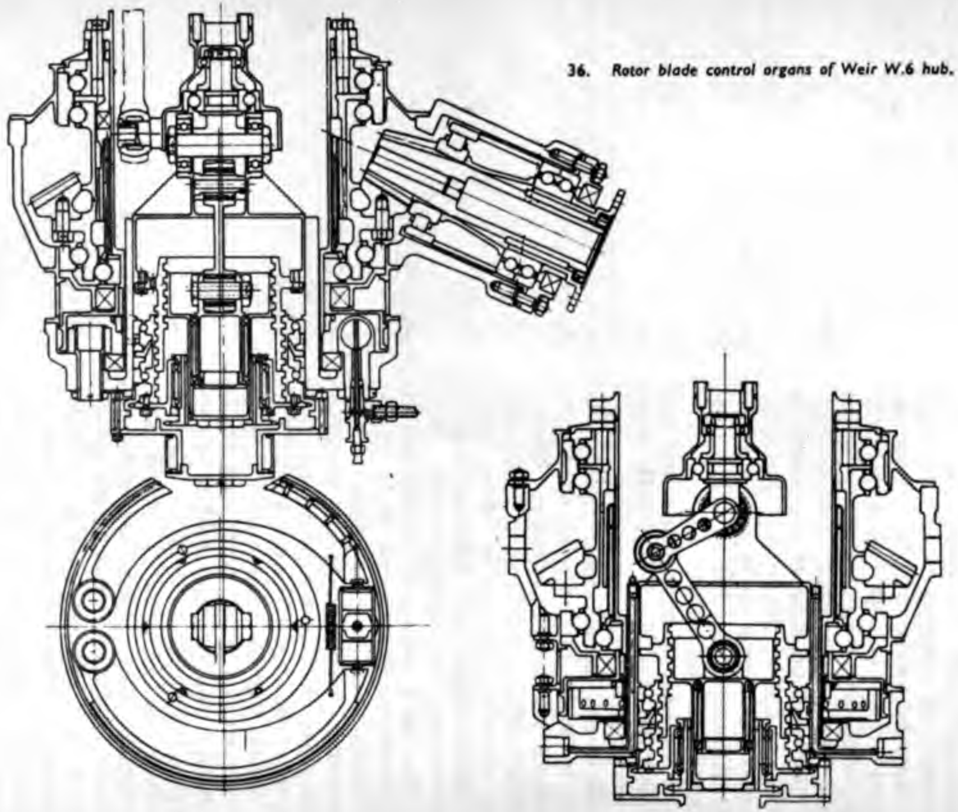
The all metal blade occupied my attention for many years and although it should be possible to evolve a design meeting with the general requirements, I must say my experiments have not been very successful. The total weight is, of course, one difficulty, it being inadvisable to have the ultimate rotor coning angle too small. Perhaps new materials and improved methods of fabrication will become available in the near future that will solve some of the associated problems but the present composite wooden blade is also undergoing further development.

Rotor Controls

One of the problems associated with rotating wing aircraft has been the moments in the pilot's control arising from the blade kinematics. Early attempts at irreversible controls on the Autogiros were unsuccessful, but the screw jack system employed on the Weir helicopters W.5 and W.6 presented no difficulties as regards pilotage.

35. Weir W.5 rotor hub mounted on machine. Observe the screw jack control to internal swash plate.

37. Weir W.6 rotor hub and blades mounted on outrigger. Note blade interbracing cables.



36. *Rotor blade control organs of Weir W.6 hub.*

Here then is an example of what is termed the "impersonal control" which, of course, is similar to that of the German Focké machines, and I believe, the Sikorsky R.5. It would have been quite an easy matter to arrange some spring resistance or "feel" to the control column but was found to be unnecessary. This was further confirmed on the Cierva helicopter W.9, which employs hydraulic servo controls super-imposed on the mechanical control, the control column being irreversible as from rotor to control column. On the other hand, the control effort is of a very low order and quite smooth in action, so that this system is likely to find favour on helicopters, more especially the larger machines. The centrifugal pitching or torsional moments of the Autogiro rotor blades are relatively small as the angle of incidence is correspondingly small, but in the case of the helicopter blades working at substantially three times the pitch setting of the Autogiro blades, the moments can be considerable. The loads arising from the centrifugal pitching moments are, of course, domestic to the rotor hub and blade articulation when cyclic pitch is in say the neutral position so that all the blades have the same pitch setting. Application of cyclic pitch gives the differential effect from which the moments arise. These remarks, with some qualification, also apply to the orientable rotor hub. The friction valve of the screw jack control when unassisted by servo mechanism has many limitations, especially on large multi rotor helicopters.

Stability and Control

Under this heading we have perhaps the outstanding problems of the helicopter. There seems to be a general impression that once the fixed wing had been replaced by the lifting rotor, any person of reasonable intelligence could enter the pilot's seat and take the air in safety and in comfort. Although I had some relevant misgivings when constructing the Weir helicopter W.5 in 1937 I did not anticipate the utter disappointment I experienced when trying to hover the Weir W.5 in the early part of 1938. I was most perplexed by the rapid rate of displacement of the machine about all axis and the pilot's control lay-out was completely inadequate. A careful investigation of the associated parameters indicated a hair trigger control system but owing to the small size of the aircraft it was thought that even then the normal pilot's reactions would be too slow to meet with the requirements. It was also apparent that the machine possessed no static stability whilst hovering and very little dynamic stability. There appeared to be no solution to the problem of static stability but the dynamic stability could be improved by increasing the moment of inertia about the pitching axis by introducing some horizontal offset of the flapping hinges together with an additional five feet added to the tail end of the fuselage. At the same time, the angle of the side outriggers carrying the rotors was changed from 11.5° to 22°. A normal control column and rudder bar replaced the rocking wheel control. The result was most satisfactory and hovering on short ropes in the erecting shed became possible although the ground interference was most marked. Shortly after this the Weir W.5 made its first free flight under full control. The data arising out of these tests was successfully employed for the Weir W.6 that was flown on the first day it was taken to the test field. Control of the aircraft, however, required much skill and practice except under conditions of translational flight when the tail

plane, positioned in undisturbed air, would provide some reasonable static stability on the phugoid path, the latter being of " easy " configuration on account of the small amount of inertia of the aircraft as a whole.

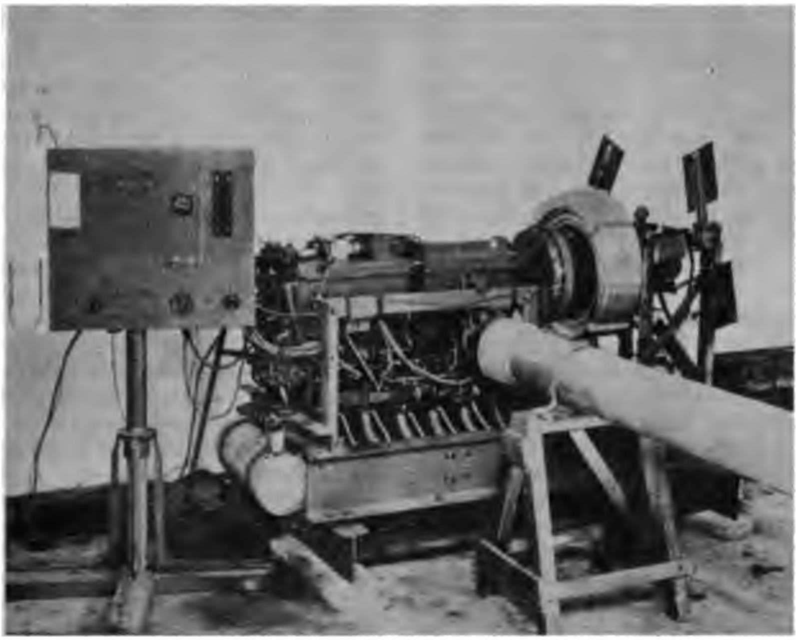
If the helicopter possessed inherent static and dynamic stability the question of control would be relatively simple and mainly that of direction. Unfortunately, we find our control system becomes a slave to the shortcomings of this attractive aerial vehicle. With my single rotor machine, some dynamic stability has been introduced by the horizontal offset of the flapping hinges which permits, when hovering, even in light winds to remove the hand from the control column for some ten to twenty seconds. Slight static stability on the phugoid path is also present. In spite of this, it appears that the aircraft must be constrained in equilibrium which calls for a very sensitive and quick acting control, also a pilot having the necessary skill and training. The pilot thus becomes the datum of " controlled stability " but this can be relieved to some extent by the horizontal offset of the flapping hinges or its equivalent in the form of some partially independent datum, as given by the Bell inertia bar constraint. The Bell system is at present limited to the use of two bladed rotor systems with the attendant problems of vibration. Perhaps the ultimate solution to the stability of the single rotor helicopter using more than two blades will be a reasonable horizontal offset of flapping hinges together with an adequate system of instrumented automatic control.

With multi-rotor helicopters such as the side-by-side, we find in the Langraf machine an arrangement that can give quite good static stability in forward flight. This is achieved by using unarticulated rotor blades together with cyclic pitch control and arranging the C.G. of the aircraft to be in front of the centroid of lift. With the Focké, Weir and Platt Le Plage machines using articulated rotor blades it becomes necessary to employ a tail plane to give a similar effect. With the tandem configuration, such as the American Piasecki or P.V. it is possible to adjust the centroid of lift so that the aircraft can be trimmed to provide some static stability in forward flight although the rotor interference introduces many secondary problems. There is very little to choose between articulated and non-articulated blades with this particular configuration. The Cierva 'Air Horse,' three rotor helicopter, appears to give the optimum arrangement and can be shown to possess sufficient dynamic stability about the pitching and rolling axes whilst hovering together with adequate static stability when in forward flight. Here again it is possible to use articulated rotor blades. Rotor interference is estimated to be appreciably less than that of the tandem arrangement.

To conclude this section, I am of the opinion that having reached the state of full appreciation of the difficulties of stability and control, the solution, although not simple, will be reached in the near future. The practical application will of necessity, differ according to the type of helicopter chosen.

Power Units

The internal combustion piston engine is a good servant but makes a bad master. My considerable experience in the design and application of piston engines to road vehicles of all types, stationary power plant and aircraft, suggests that though this form of prime mover has great versatility, nevertheless, every application needs individual study. Some years ago I designed a small two cylinder



Power unit of Weir W.6 complete with fluid flywheel cooling fan and power distribution box with fan brakes. The large tube is attached to the carburettor air intake.

opposed engine for use on the early light aeroplanes which gave quite reasonable service until it was decided to introduce a reduction gear between the airscrew and crankshaft. Amplification of the torque peaks through the gears either resulted in broken crankshafts, damaged gears or fretting of the splined shafts. The power output was also lower than calculated. In spite of past experience, I was asked to design a two cylinder geared engine as late as 1933. To keep the aircraft flying it was necessary to introduce a special device to damp out the torque peaks associated with this type of engine. The additional weight and cost of this damping component ruled out the installation as uneconomical. For the first Weir helicopter W.5, I used, purely on the score of economy, the small four cylinder in-line air cooled engine that I designed in 1935-36 for the light single seater Autogiros. Fortunately, the crankshaft was exceptionally robust and managed to stand the racket for the relatively short life of the experimental aircraft. The overall gear ratio between engine and rotors was 8.4 to 1 so that trouble with torsional vibrations was to be expected. No doubt the long transmission shafts damping effect in the numerous bearings and the elastic constraint of the rotor blades in relation to the rotor hubs, played an important part as no trouble was experienced.

For the Weir helicopter W.6, employing a Gipsy Six engine, with its relatively long crankshaft, the difficulty was met by the fitting of a Fottinger coupling fluid flywheel.

In practice this was found to give very good results and also provided a most satisfactory hydraulic rotor starting clutch in the following manner. The low speed drag of the coupling was resisted by a transmission brake which when released, would allow the engine to progressively start the rotor. Increase of engine speed would bring the coupling into full operation with a final slip of some 3%. On the research machine Cierva W.9, the fluid flywheel was not included and evidence of the amplification of the torque peaks is present in the form of fretting of the centralising cones holding the clutch component on to the crankshaft, also on the teeth of the secondary reduction gear pinions. This does not only apply to the Cierva W.9, but it is found on other helicopters now in use. I anticipate an improvement with the Rolls Merlin engine proposed for the large Cierva three rotor helicopters now under construction, mainly on account of the large number of cylinders and the short stiff crankshaft. I am not prepared at this juncture, to suggest a formula of the application of the Internal Combustion Piston Engine to the helicopter, but it is just possible that by taking into account all the relevant parameters, it might eventually be deduced to simple terms, an important factor being the piston head area. A full explanation is somewhat involved, but I have a case in mind where a low speed engine was replaced by a high speed engine having a 25% increase power output. In spite of careful adjustment of the associated components and the rotor system, the performance of the aircraft was not improved, or we might say, that the additional power of the high speed engine was not doing the additional work on the air. What I have just outlined indicates the difficulties of finding a suitable power unit for the light two seater helicopter that will have a low purchase figure together with reliable operation and small maintenance.

Whilst on the question of piston engines my practical experience leads me to favour the liquid cooled engine together with a liquid cooled exhaust manifold as being the most economic solution to the problem of the submerged engine as is generally the case with the helicopter. Fan cooling of the Gipsy Six in the Weir W.6 absorbed some 8% of the maximum power. The installation of the same engine in the Cierva W.9 is so arranged that adequate cooling is achieved for approximately 3.25% of the maximum power, but in this case it represents part of the thermo dynamic cycle employed for rotor torque balance system.

39. *Cierva W.9 power unit on assembly stand. Note engine cooling boost fan.*

Liquid cooling of the Rolls Merlin for the Cierva Air Horse is calculated at less than 2½%. The modern high efficiency axial flow fan and heat exchanger permits the heat to be extracted in the most scientific manner. A large percentage of the weight of the cooling installation is

cancelled by the reactive thrust of the cooling fan.

Air cooling of the exhaust manifold of the submerged engine presents a difficult problem more especially as the rotor slip stream velocity is insufficient for the purpose. To avoid local hot spots is very wasteful as regards fan horse power and such hot spots represent a potential fire hazard if drops of oil are present or airborne to the localities. Instances of this have already been observed. The obvious solution is to liquid cool the exhaust manifold and a full scale engine has already successfully passed some comprehensive tests. The heat to be removed to reduce the temperature to a reasonable degree and to avoid evaporation is slightly more than that dissipated by the engine cylinders. A safe and readily controllable means of cabin heating by hot liquid also becomes available. Silencing of the engine exhaust of helicopters must also receive attention. The noise level of the lifting rotor is exceptionally low as compared with the airscrew of the normal fixed wing aircraft, the outstanding noise being that of the engine exhaust. The energy in the exhaust gasses is mainly in the form of heat so that by liquid cooling the manifold the major part of the silencing will have been carried out. Further, the ultimate temperature of the gas leaving the manifold will permit the use of aluminium alloy for the final exhaust silencer.

Burning out, distortion and cracking of present day exhaust manifolds is a constant source of worry. Special non-oxidising alloys must be used which are costly and require considerable skill in fabrication.

I cannot leave this subject without referring to the gas turbine. The type I have in mind is that in which power is taken from the turbine shaft. Patents for which I applied in 1943 indicate a practical design study covering the use of the geared turbine. The high velocity turbine exhaust, in conjunction an augmentor fan is used for torque balance in a somewhat similar manner to that employed in the Cierva helicopter W.9. Investigations have also been made into the use of single and twin turbine installation for the Cierva large three rotor Air Horse, and when such units are available it appears that taking everything into account and in spite of the increased fuel consumption over that of the piston engine, the advantage is in favour of the turbine installation up to some 2½ to 3 hours cruising. A direct analogy to this, of course, is comparison between the present petrol engine and the Diesel cycle, or in other words, the effect of compression ratio.

TRANSMISSION.

I find it impossible to deal but briefly with transmission on account of the time at my disposal. It will, however, be appreciated that 14 years' experience in this connection has resulted in a background of knowledge, which at this juncture is of the utmost value. Long transmission shafts present no difficulty if carefully designed and applied. No failure on this account was recorded with the relatively crude arrangement on the Weir helicopters W.5 and W.6. With the single rotor machine such as W.9, the solution is, of course, quite simple. Improved methods for production of long, straight, large diameter tubes would be welcomed.

I should perhaps mention the torque metre used on the Cierva W.9 in 1944-45 which is no doubt the first time that such a device has been used on the helicopter. The torque was measured by the very small torsional deflection of the main rotor shaft and amplified through two sets

40. *Weir W.6 rotor hub gears and ratchet free-wheels to give correct phasing of rotors.*

41. *Weir W.6 torque distribution box. Of special interest is the constant speed unit mounted on the left hand top side and the torque breakdown device at opposite end.*

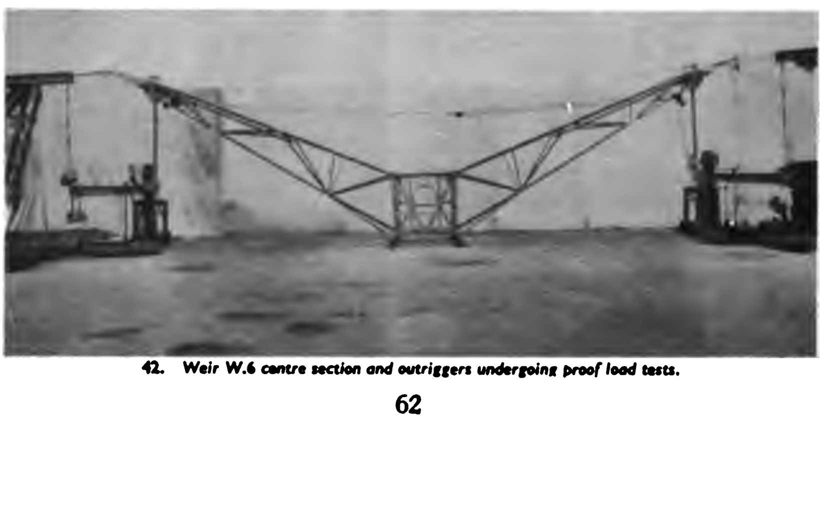
of planetary gear train, the deflection being magnified ten times so as to give a direct reading in a calibrated dial in the pilot's cockpit. This apparatus provided the means to check the power applied to the rotor and tail jet, also permitted a close check of the rotor efficiency.

Undercarriages.

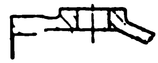
Practical operation of Autogiros and helicopters with which I have been associated bring into prominence the rather serious hazard of mechanical failure when hovering or slow flying up to 200 feet above the ground. In 1939 I provisionally protected the use of the kinetic energy stored in the rotor to cushion out the landing when a few feet from the ground. Unfortunately, this provisional patent was allowed to lapse. The principle, however, is in use today and is perhaps the saving grace of the present helicopter in case of emergency. To use this effect to advantage, it has been found possible to design apparatus that is automatic in effect to give the optimum rate of descent either as a helicopter or when under autorotation. Pure vertical landing can be accommodated by a long travel undercarriage, which in the case of the large Cierva 'Air Horse' is 5 feet. The travel, of course, depends mainly on the disc loading of the particular machine. For the single rotor type of machine this is met in a somewhat similar manner by the employment of a special form of duplex undercarriage giving the same long travel effect but having the appearance of a normal configuration.

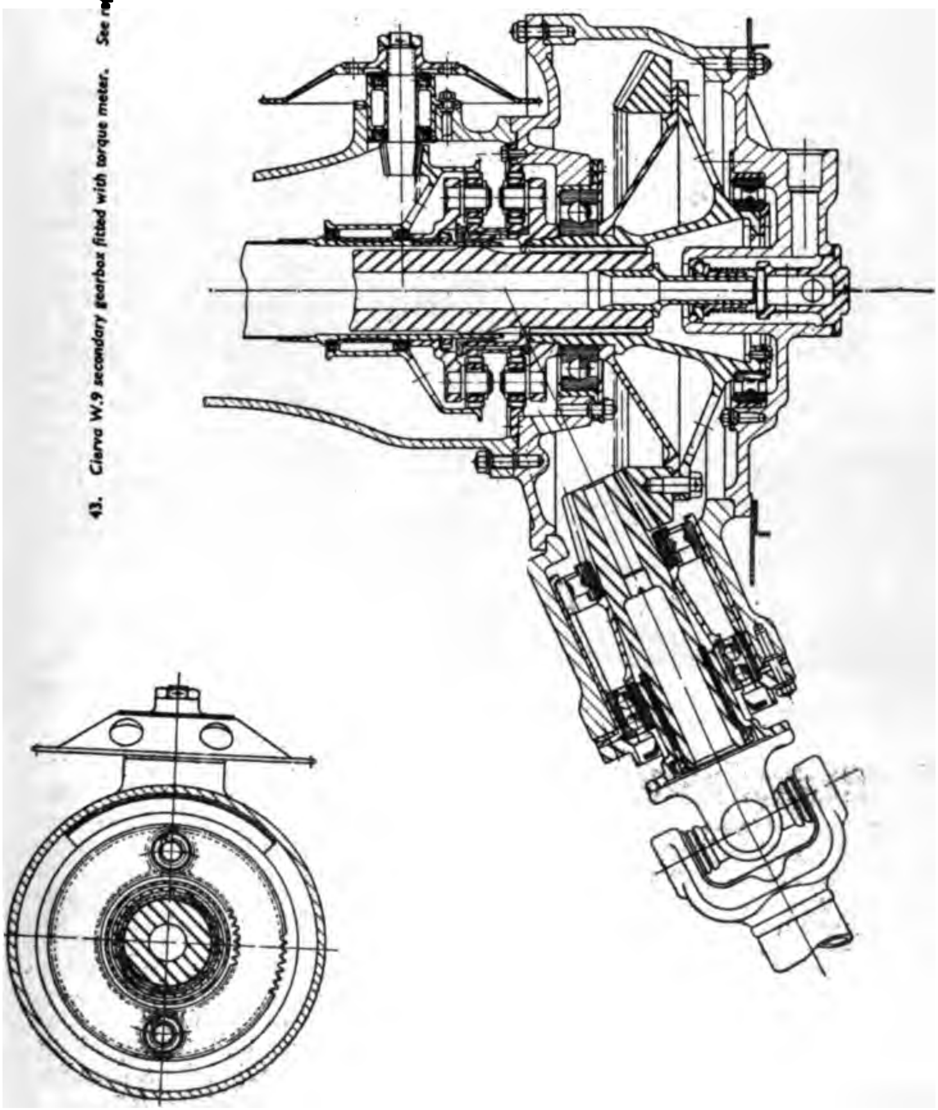
MECHANICAL DETAILS.

If time permits I hope to show on the screen a few mechanical

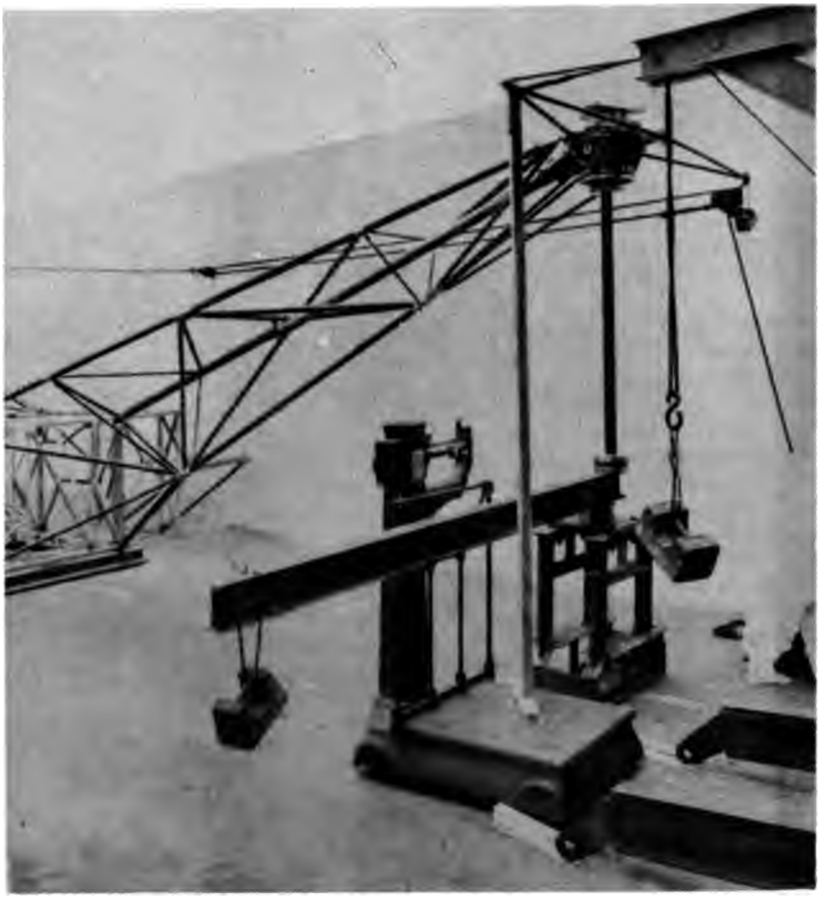


42. *Weir W.6 centre section and outriggers undergoing proof load tests.*





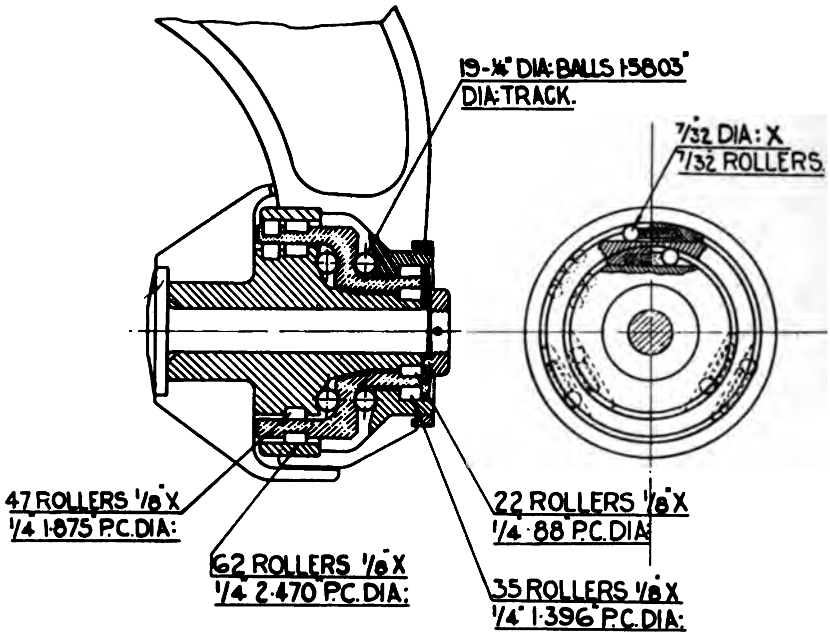
43. Cierva W.9 secondary gearbox fitted with torque meter. See reference in text.



44. *Close up view of loading device employed for proof test of Weir W.6 centre section and outriggers.*

details which may be of interest to the audience and gives some idea of the intensive research that has taken place in the past years.

One very important component of the rotor system employing cyclic pitch control, also the orientable hub with Delta III blade coupling, is the torsion bearing of the rotor blade. In the case of the Autogiro angled hinge system, reasonable control effort was only possible when the plain bearings had been replaced by ball or roller bearings. Unfortunately, the small order of pitch oscillation during flight, some $\pm 1\frac{1}{2}$ degrees, caused the balls to Brinell the race tracks, thus increasing the frictional moment of the bearing and introducing considerable roughness in the system. Roller bearings were also found to be unsatisfactory on many counts. To keep the overall friction down to the minimum it was necessary to secure correct geometrical rolling of the balls and this was accomplished by the use of specially formed V



64. Inching bearing pack for thrust loads under small torsional oscillations.

grooved tracks. By arranging a pair of the V grooved races in tandem and by the application of the roller free wheel principle, the oscilations would cause the pair of races to " inch " round under load and so eliminate the indentation of the race tracks. Many hundreds of hours of full load testing proved the bearing to be highly satisfactory. It was completely reliable and would respond to small oscilations of $\pm$ 20 minutes. The frictional moment was approximately half of that of a new and normal ball thrust race, the friction actually becoming less after the first 50 hours before levelling off to remain constant over some 500 hours. A drawing of this bearing is included which gives details of the design. There is no doubt that the bearing pack could be used to advantage on the helicopter in spite of the pitch oscilation being of a much larger order. The very low frictional moment would be most helpful, especially on the large machine.

Odd Types

I should have liked to have given my experience in the theoretical investigation and practical design of such types as the Gyrodyne, the reactive propulsion rotor of helicopter W.8, and the rocket assisted Autogiro/helicopter now being developed by the Autogiro Company of America, but this I am afraid must be left to a later date.

Conclusion

In conclusion, the helicopter is with us in many practical forms, but of course, utilising the same basic principle. It should be deprecated that we are at present saddled with considerable complexity but this appears to be the case in the development of most

simple machines in the search for efficiency and to bring them within practical scope. I can instance many examples, including the simple 3 port 2 stroke engine, the thermodynamic duct or ram jet which we now see in the form of the gas turbine and sometimes for jet propulsion. The trend in design is towards further complexity but thanks to the excellent work of the A.I.D. we should have no fears in this connection, confirmation of which is given by the mass production of the most delicate apparatus, aircraft engines and components not only in this country but throughthe world. As long as the A.I.D. are with us, or alternatively, the Civil version the A.R.B. we can look forward in confidence to the successful and safe operation of helicopter aircraft.

As regards operational costs, I find that the large three rotor helicopter can carry freight at a lower cost than that of the equivalent fixed wing aircraft, this, of course, taking everything into account including maintenance, airfields, etc., but at a reduced speed. In other words, we must pay for speed, although for short distances even the speed can be in favour of the helicopter.

It will be noted that I have not confined my attention to one configuration of helicopter. At the present state of the 'art' constructional and other limitations impose restrictions on rotor diameters, so for useful loads of over 1,000 lbs. we should employ multi-rotors. Careful calculations indicate an overall gain in efficiency by keeping the rotor diameter within reasonable limits. At present I have design studies in hand covering light two place single rotor helicopters, 2 up to 5 place single rotor machines with reactive thrust torque balance, three rotor passenger and freight helicopters up to payloads of 3 to 4 tons and even larger four rotor types to lift 8 to 9 tons. Even the tandem configuration and improved Gyrodyne has not been forgotten. Once the complete rotor circulation under all regimes of flight is properly understood, the pieces of the jigsaw puzzle begin to fall nicely into place. Perhaps the best visual experience I had as regards circulation, was during the recent crop spraying tests by Messrs. Pest Control Ltd., on a helicopter suitably equipped by the Cierva Autogiro Co., Ltd. I shall one day endeavour to obtain a photographic record of this rather puzzling phenomenon.

Finally, the time factor is not on the side of those engaged in the art and everything possible should be done to get practical helicopters into service without delay. No one can say at this juncture, how long it will be before we shall have control of the release of atomic energy and if and when this is secured the whole aspect of aerial flight and aerial machines may be subjected to a drastic change.

I trust that the ambitious student will find some pointers in this paper that may help to unravel some of the problems of design and eliminate disappointment.

Mr. Chairman, Ladies & Gentlemen,

I thank you for your attention.

Mr. H. A. Marsh—Chairman.

Ladies & Gentlemen,

I feel sure you have thoroughly enjoyed Mr. Pullin's very interesting lecture and I call upon Mr. Norman Hill to propose a vote of thanks. I would remind you that some time has been allowed for dis cussion. Mr. Pullin will be very pleased to answer any questions,

Mr. O. L. L. Fitzwilliams (Member)

Enquired as to the location of the freewheel component in the Cierva W.9 which he understood was in the rotor hub. This was confirmed by Mr. Pullin and the reasons given as to the choice of location. Its relationship to the rate of vertical descent is now included in the text.

Mr. R. G. Robertson (Member).

Was it not a fact that some years ago experiments were carried out with the use of aerofoil surfaces fore and aft on the fuselage in the vertical plane for torque correction?

Mr. Pullin agreed that such tests had been conducted (see text) but as he aimed at a stable fuselage the aerodynamic surfaces were confined to that portion of the fuselage behind the rotor pylon. In any case, the symmetrical arrangement would suffer in the same manner as the non-symmetrical model.

Major H. O. Nelson (Member).

Have any experiments been carried out with variable sections on a rotor blade?

Mr. Pullin assumed that Major Nelson referred to a variation of the section as from root to tip. Comprehensive tests were conducted on the Autogiro but the results were only marginal and did not warrant the constructional difficulties. On the other hand, the moulded blades on the Cierva had the adequate variation.

Dr. Hislop.

Should the constant speed unit be applied to the engine throttle or to the rotor pitch control?

Mr. Pullin gave his views and thought that in the hands of a skilled pilot the constant speed unit should be applied to the engine throttle. This unfortunately placed the onus of change over from helicopter to autorotation on the pilot. As applied to the rotor, precision flying close to the ground was impaired owing to the limitation of engine power and the moment of inertia of the rotor. He was experimenting with a combination of the two systems including an automatic change over.

Group Captain Howard.

Raised the question of the danger period when hovering between 30 and 300 feet. He thought that an increase in the weight of the rotor blades would make more kinetic energy available for emergency landings.

Mr. Pullin agreed that this could be done but the possible increase of blade weight would not give sufficient kinetic energy to meet the case. The long travel undercarriage appeared to be the best solution at this juncture.

Mr. O. Vines (Member):

Does the plastic material referred to for rotor blade finish adhere to wood and metal?

Mr. Pullin: Provided the wood or metal is virgin material, i.e. not having been previously painted or treated, the plastic will adhere in a satisfactory manner.

A Visitor:

Asked for an explanation as to the inclusion of a constant velocity joint in the Cierva W.9.

Mr. Pullin explained the Hooke's joint effect and how it was associated with the rotor hubs of helicopters.

Mr. L. S. Wijdortchich (Member).

Enquired as to the time lag of the reactive thrust yawing control.

Mr. Pullin explained that the time lag on the Cierva W.9 was approximately .75 second but did not affect the hovering flight to any appreciable extent. W.9 was a pure research machine but the resultant design study had reduced this lag to under .3 second.

Dr. Hislop:

Was anything being done to improve the longitudinal stability of single rotor helicopters?

Mr. Pullin stated that the Cierva W.9 had been designed with quite a large horizontal offset of flapping hinges for this purpose. A full report will be issued in due course.

Mr. F. H. Dixon (*Member*):

Had experiments been carried out with deflecting the tail jet for torque control while maintaining constant reaction.

Mr. Pullin pointed out that the Cierva W.9 is fitted with tail jet deflectors which can effect the trim about the pitching and rolling axes at the same time as giving torque balance. The direct control of fuselage attitude about the pitching axis was most useful as regards C.G. shift.

Mr. Garraway (*Member*):

Owing to scale effect, was the data obtained from models reliable?

Mr. Pullin replied that quantative data, except for direct comparison with other models of similar scale should not be regarded as of practical use. On the other hand, qualative information was most valuable and instructive. It could save time and money when related to full scale tests.

Mr. F. H. Dixon:

Written question.

Dear Mr. Pullin,

In thanking you for the most interesting lecture which you gave us last week, there is one question which I should like to have put to you before the meeting closed. Possibly you may be able to answer it in the report of the lecture:—Would it be opportune to give us some figures for duration, height and distance, established by the W.5 and W.6 during the flight trials? In view of the historical importance of the work done by yourself I feel that these data would be of great interest to all of us.

Yours sincerely,

Signed F. H. Dixon.

Mr. Pullin:

In response to Mr. F. H. Dixon's letter I have included a brief history sheet of the flying of the Weir helicopters, W.5 and W.6.

MAKING HISTORY.

G. & J. Weir, Ltd.
Cathcart,
GLASGOW. Licencees of the Cierva Autogiro Co. Ltd. Co. Ltd.

HELICOPTER W.5

Designed and constructed by Messrs. G. & J. Weir, Ltd.

Chief Designer—Mr. C. G. Pullin
Test Pilot—Mr. R. A. Pullin.

Brief Specification:

Single seater fuselage carrying outriggers on either of the fuselage supporting two bladed rotor hubs. Cyclic and collective pitch control. Rotor diameters 24 feet running at 435 r.p.m. Powered by Weir 50 h.p. 4 cylinder in-line aircooled engine (blower cooled).

All-up weight 860 lbs.

Design commenced in October 1937 and first free flight at Dalrymple June 6th 1938.

This was Great Britain's first successful helicopter and apart from the German Focké machine, flying at the same time, was the world's second successful helicopter. It was and still remains the smallest and lowest powered helicopter to give flight demonstrations to officials of the M.A.P. etc.

Over one hundred power take-offs and landings were made and the pilot's licence endorsed for helicopter flight. Maximum speed as checked at Dalrymple was 70 m.p.h.

Rate of climb not measured but estimated to be 400 ft./sec. at 30 m.p.h.

The machine could fly forwards, backwards, sideways and rotate about the yawing axis.

This aircraft was in use most of the time between June 1938 and July 1939.

The flying of this helicopter was of necessity confined to the precincts of the aerodrome or football field but the log book indicated a total of some 78 flying hours. Component parts are still in existence.

HELICOPTER W.6

Designed and constructed by Messrs. G. & J. Weir Ltd.

Chief Designer—Mr. C. G. Pullin.
Test Pilot—Mr. R. A. Pullin.

Brief Specification:

Two seater tandem fuselage carrying outriggers on either side of the fuselage supporting the three bladed rotor hubs. Cyclic and collective pitch control. Rotor diameter 26 feet running at 275 r.p.m. Powered by Gipsy VI Series II engines, blower cooled by Weir. Fluid flywheel included in transmission line. Constant speed unit fitted to rotor and automatic change-over to autorotation.

All-up weight 2360 lbs. (unfaired) Design commenced in October 1938 and made first flight October 27th 1939. This was the world's first successful two seater helicopter. On the 28th October 1939 the machine established a further record by carrying two passengers, besides the pilot.

Maximum speed was not checked owing to the wartime restrictions on airfields and the test flying was confined to waste land at the Argus Foundry, Thornliebank, Glasgow. It was estimated that the speed in a closed circuit was in the region of 80 m.p.h. with a calculated maximum of 90 m.p.h. Rate of climb at 25 m.p.h. was 650 ft./sec.

The machine could fly forwards, backwards, sideways and rotate about the yawing axis.

Flight tests were in progress from October 27th 1939 to July 1940 when the Department was disbanded owing to the unfavourable turn of the war. A total of some 70 hours flying was recorded.

The component parts of this aircraft are still in existence but the Gipsy engine was installed in the Cierva W.9.

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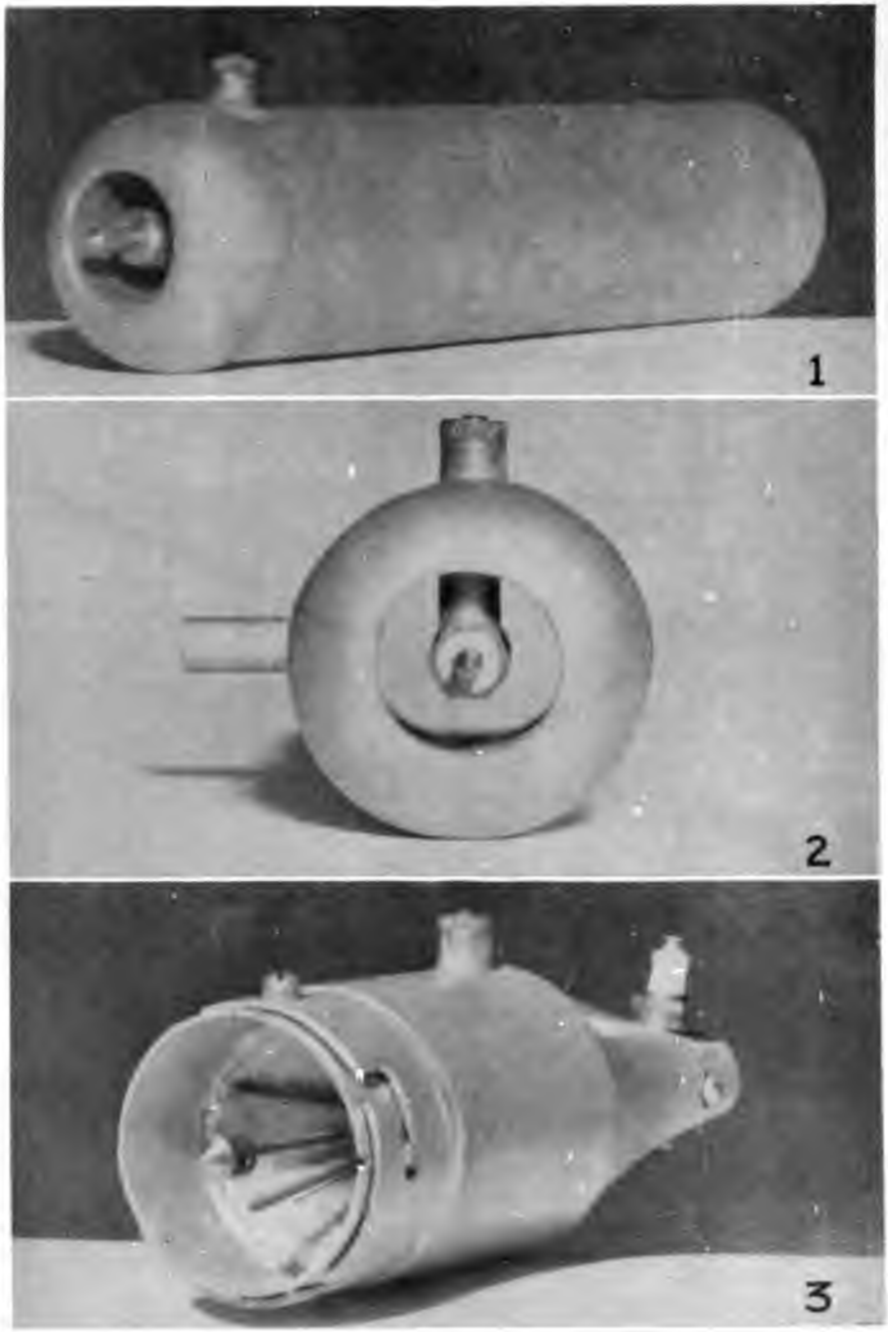
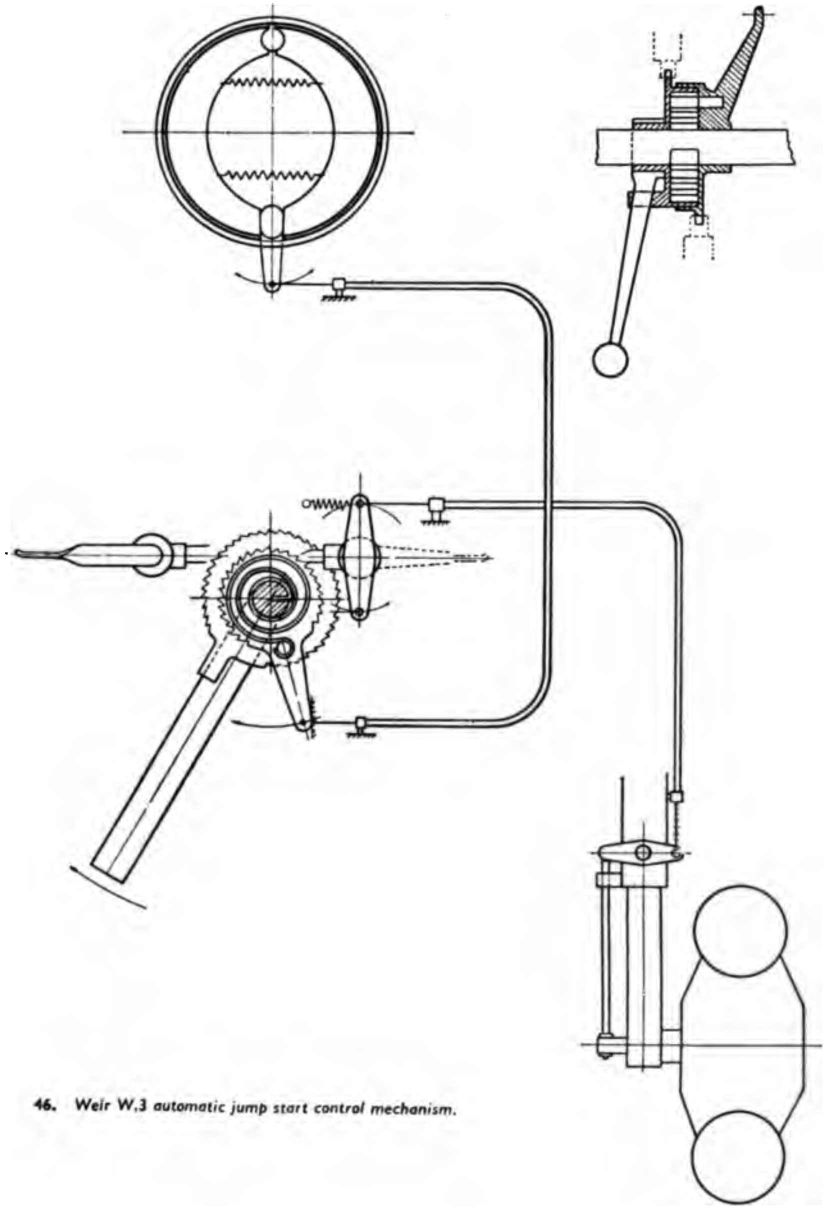
59 (top). A small ram jet unit for experimental test. (Made to drawings and instructions issued by the Aircraft Jet and Rocket Corp., U.S.A.).

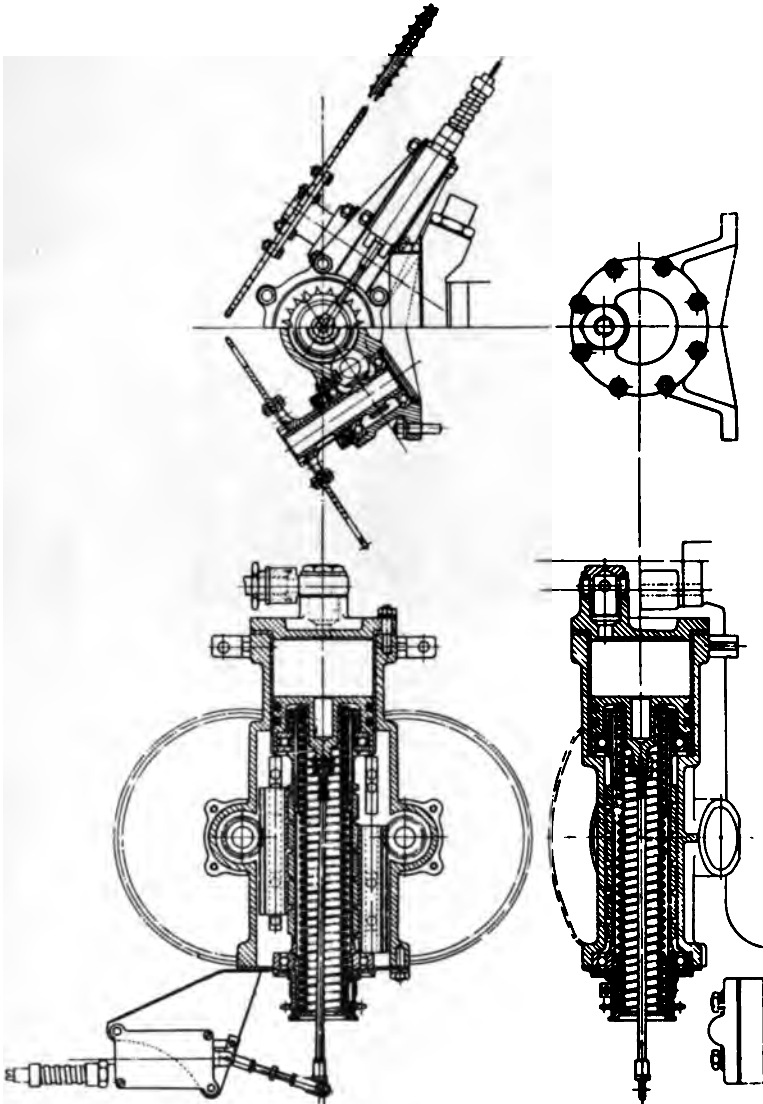
60 (centre). End view of ram jet unit depicted in 59. The stub on the left hand side is for mounting on the rotor a.m. Fuel is contained in the surrounding jacket.

61 (below). A jet unit of the impulse type. Note the flap valves at intake end. (Made to drawings issued by the Aircraft Jet and Rocket Corp., U.S.A.).

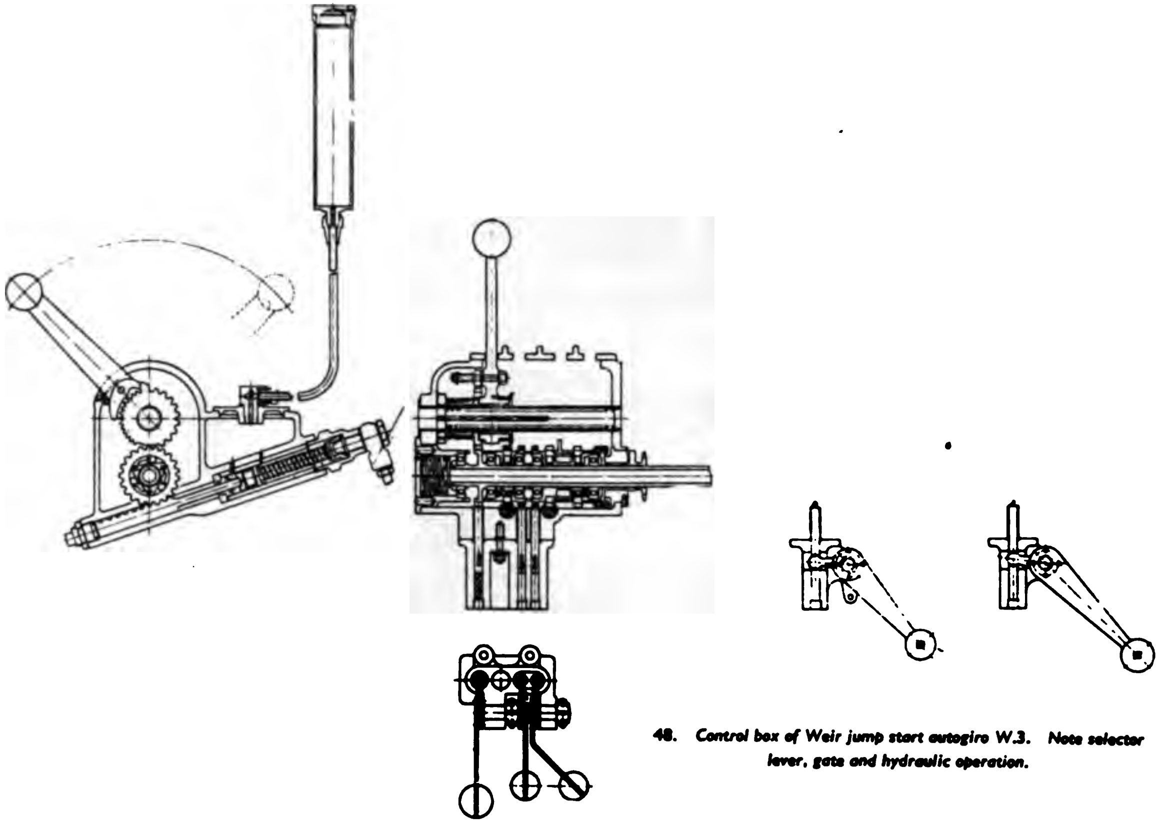




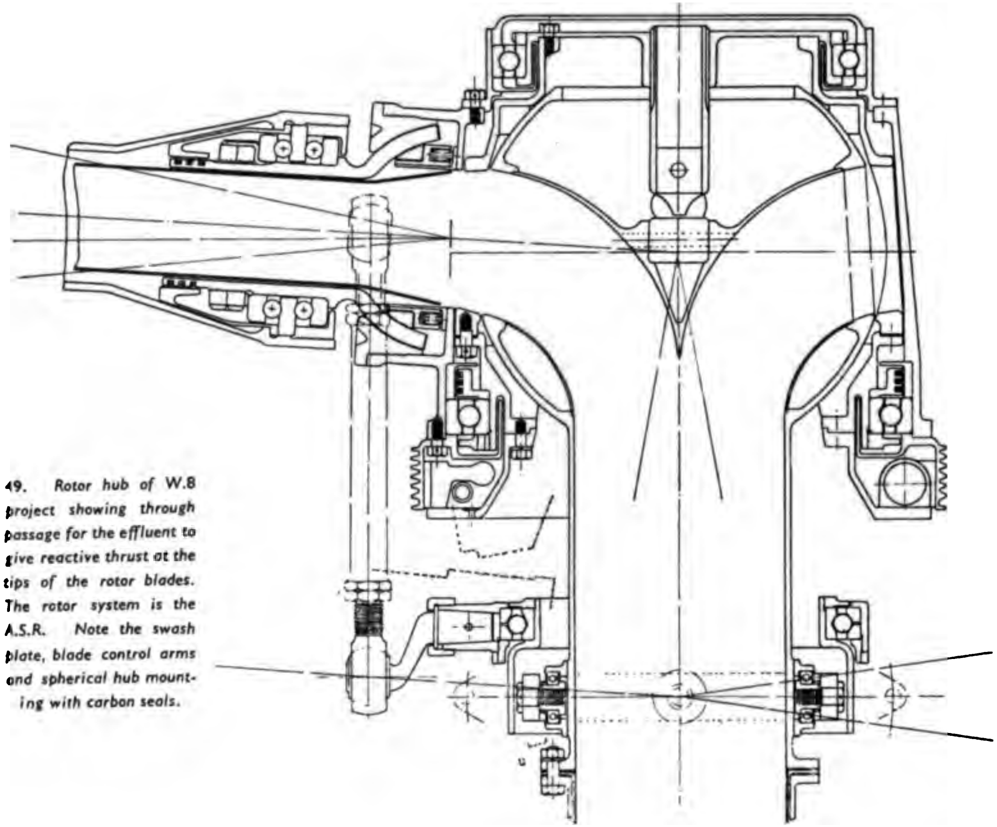
46. *Weir W.3 automatic jump start control mechanism.*



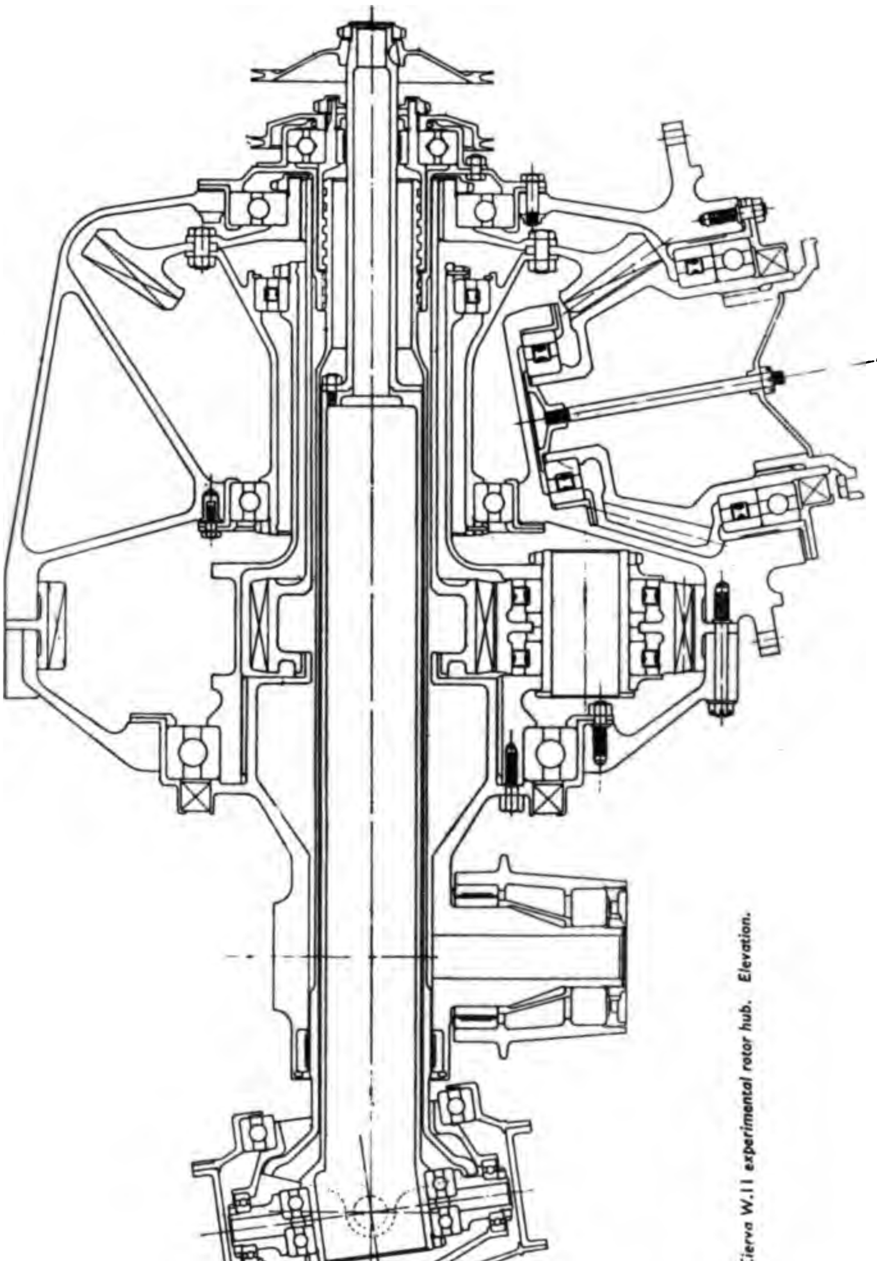
45. Weir W.6 control box with hydraulic change over device to autorotation on rotor speed change.



48. *Control box of Weir jump start autogiro W.3. Note selector lever, gate and hydraulic operation.*



49. *Rotor hub of W.8 project showing through passage for the effluent to give reactive thrust at the tips of the rotor blades. The rotor system is the A.S.R. Note the swash plate, blade control arms and spherical hub mounting with carbon seals.*

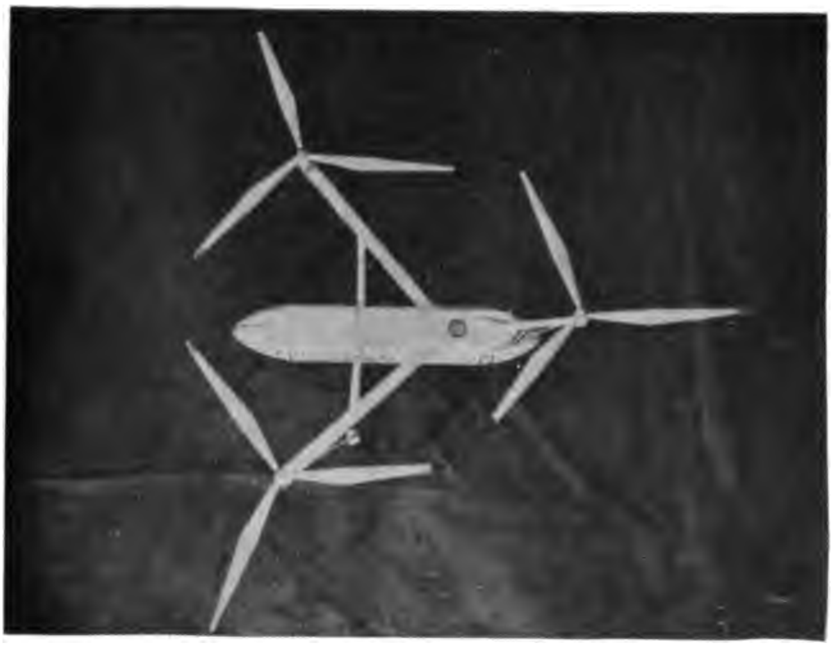


50. Cierva W.11 experimental rotor hub. Elevation.

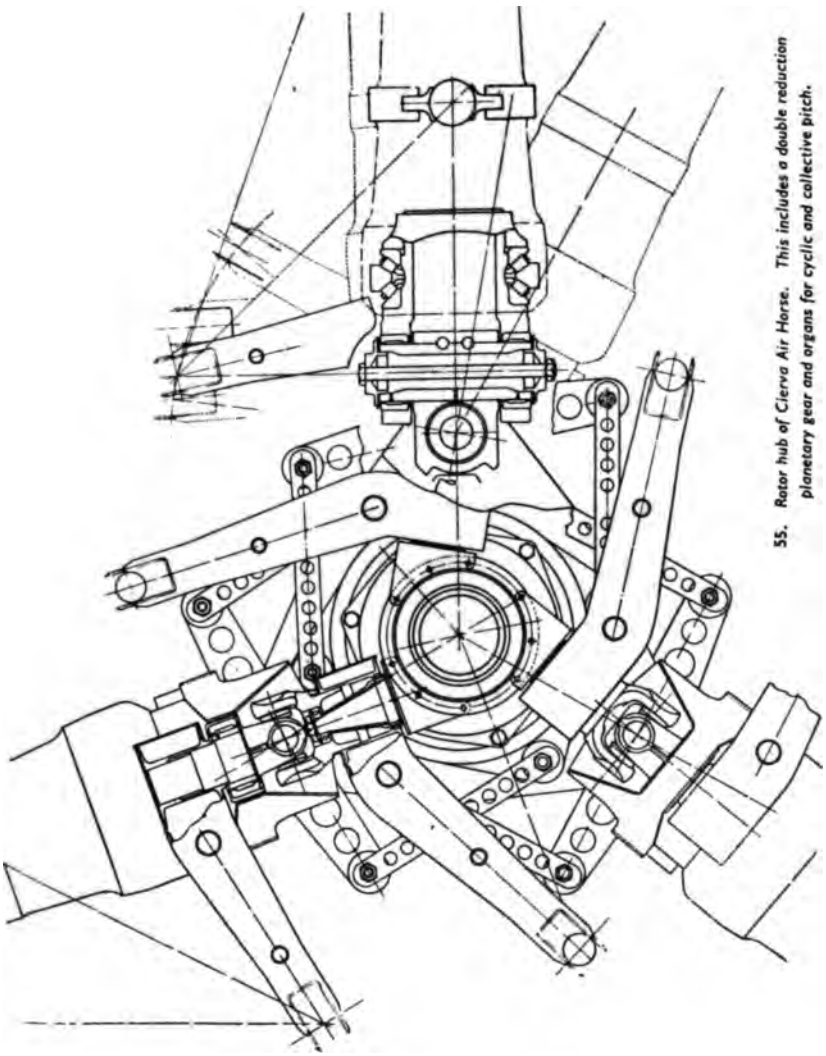
51. W.11 Air Horse model. The full scale machine is now under construction. With Rolls Royce Merlin engine this aircraft will have a payload of three tons.

52. Cierva Air Horse, freighter version. Note rear loading doors and ramp.

53. *Cierva Air Horse* (W.11) *as a* 24 *passenger machine excluding crew.*



54. *Plan of Cierva Air Horse. The air duct for engine cooling will be noted on the top front end of the fuselage.*



55. Rotor hub of Cierva Air Horse. This includes a double reduction planetary gear and organs for cyclic and collective pitch.

HELICOPTER W.6.

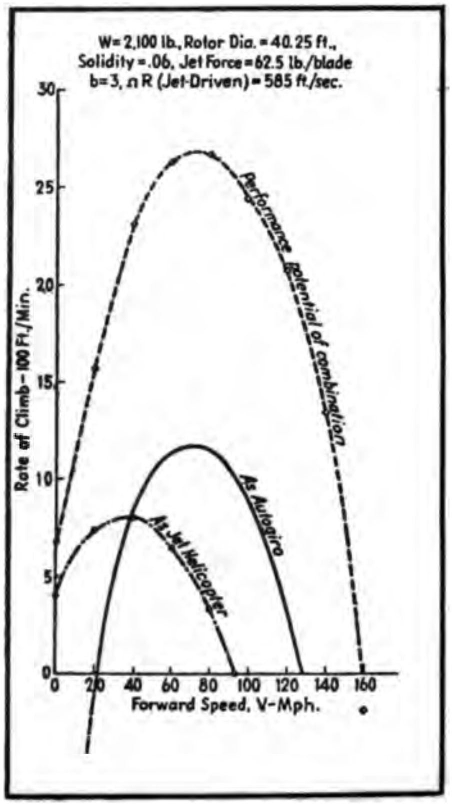
This is to certify that the undersigned have flown in the above machine as passengers

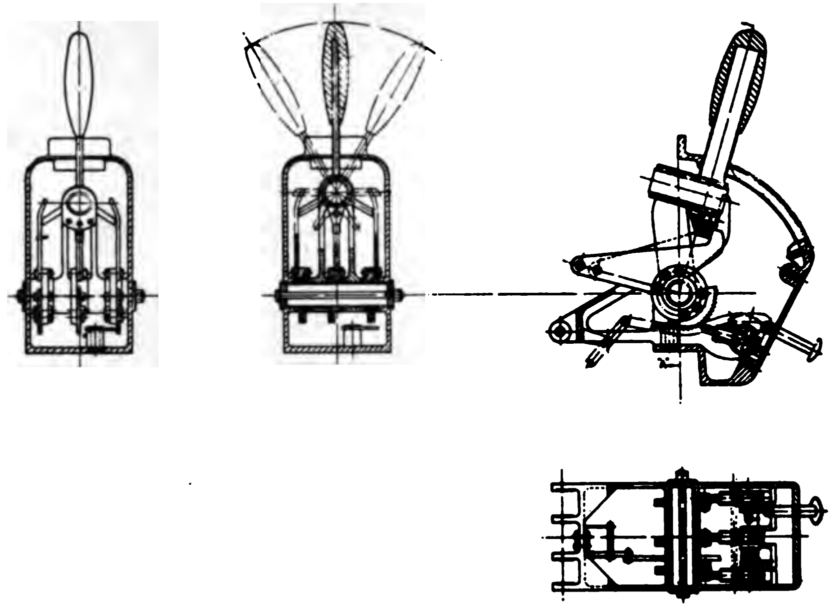
Pilot [illegible]

NAME	DATE	TIME	REMARKS
H. Watson	27-10-39	11 30 a.m.	Machine takes off very smooth " Mechanically " "
J G Weir	27.10.39	11 45 a.m.	machine very smooth. Yes some what [illegible]
L. Pullin R McLean	28.10.39	10.45 a.m.	Both passengers in the front cockpit 300 lbs
[illegible]	28.10.39	10.55 a.m.	Very nice
[illegible]	28.10.39	11.0 a.m.	Bumpy weather machine very smooth.
R.J. Bowyer	28 10 39	11 5 a.m.	No wind Very pleasant
[illegible]	28.10.39	11-10 a.m.	Smooth
H. Watson	28-10-39	11-15 a.m.	Mach. checked first complete yaw. about vertical axis
J [illegible]	28 10 39	11-15 a.m.	First aerial photograph taken from front cockpit of a helicopter
L. Pullin	31.10 39	12.13 [illegible]	Taxiing in gusty weather 15 to 30 m.p.h. Port rotor blade came off machine.
R.N. Liptrot	15 2 40	11 a.m.	Rather Gusty Rotors Smooth
J.G. Bennett	15.2.40	11.15 a.m.	Very Gusty Weather Machine Smooth
Air Chief Marshall Tedder	25-2-[illegible]	11 30 a.m.	Bad Weather Machine Smooth

56. (above). Record of passengers carried on Weir W.6 helicopter. It will be noted that the first passenger was carried on 27/10/39. On the following day the machine was flown with two passengers and pilot. Many well known names are included in the list.

57. First aerial photograph taken from a helicopter. The group includes the designer and his staff outside the hanger on 28/10/39.





47. *Control box of Weir jump start autogiro. Note selector lever and gate.*

58 *Curves showing autogiro with jet assisted rotor. Project of The Autogiro Company of America (by kind permission of Mr. Paul Stanley, Chief Engineer, Autogiro Company of America, and as illustrated in the U.S.A. magazine "AVIATION."*

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Some Problems of Helicopter Operation and their Influence on Design

By Wing Cdr. REGINALD BRIE, A.F.R.Ae.S.

A lecture presented to the Helicopter Association of Gt. Britain on Saturday, 18th January, 1947, at Manson House, 26, Portland Place, London, W.1.

H. A. MARSH, A.F.C., A.F.R.Ae.S., IN THE CHAIR.

Introduction by the Chairman.

It gives me very great pleasure to introduce our lecturer this afternoon, r. R. A. C. Brie. I do feel that an introduction is unnecessary as most you will either know him personally or most certainly have heard of his ings from time to time.

Mr. Brie has been one of the foremost exponents of rotary wing flight ice 1930 during which time he has never lost an opportunity of spreading e gospel of rotary wing aircraft both by word and deed and has a number very interesting and successful flights to his credit.

He is a Founder Member of our Association and if I had my way uld have been its first Chairman. He is also a Founder Member of the nerican Helicopter Society and of a peculiar tribe known as the "Twirley rds," also of America.

It was my good fortune to work very closely with Mr. Brie for some ars before the war and there is no one better fitted to talk to us on the oject he has chosen.

Wing Cdr. REGINALD BRIE

Mr. Chairman, Fellow Members, and Guests:

Time flies with such rapidity that in our efforts to keep pace with the present we are somewhat apt to overlook the past. I feel it appropriate therefore in the opening stages of my lecture to recall that it is almost a quarter of a century since the first successful Autogiro flight was accomplished. On January 9th, 1923, Lt. Alejandro Gomez Spencer, a Spanish Army officer, flew the fourth full scale Autogiro to be constructed steadily across the Getafe Airfield at Madrid, and landed safely.

This unique event opened up a new chapter in the field of aeronautics, and although its significance may not have been generally appreciated at the time, it is fortunate that there was one man at least, the creator of this aircraft, who had no doubts on the matter. With infinite faith, patience and skill, he thereupon set about finding ways and means of solving the many secondary and highly complex aerodynamic and engineering problems associated with this unorthodox method of flight. How well he succeeded during the years following is apparent to all, for now the fruits of exploitation resulting from that historic achievement are about to be realised.

It appears fitting, therefore, at meetings such as these when we meet to discuss one or the other of the many aspects of rotary wing flight, that we should occasionally pause to pay tribute to such pioneering efforts; and in particular to direct our thoughts to the one man (alas, no longer with us) whose creative ability and genius not only made possible the Autogiro; but whose foresight and tenacity of purpose also so well and truly laid the foundations upon which the helicopter now so surely stands. I refer of course to Juan de la Cierva.

To the not-so-well informed, the gyroplane—of which type of freely rotating wing aircraft the Autogiro is the classic example—has had its day. On the other hand there are many well informed and expert in the art who believe that it has not yet been developed to the fullest possible extent. To that I shall revert later, but it will suffice for the moment to emphasize that no helicopter could be considered a safe, let alone a practical proposition, unless, in the event of power failure, its main rotor system was capable of autorotation. Under those conditions it is, to all intents and purposes an Autogiro. It is also significant that the most successful helicopter configurations to date embody basic gyroplane features in their design.

Although it is reasonable therefore to consider the helicopter as a logical development of the gyroplane, that does not necessarily mean to say that that development has proceeded along entirely rational lines. Whether the helicopter as such is a better type of aircraft than the gyroplane depends to a great extent on the point of view forming the basis for such an assumption. Not only is it more complex mechanically, but it is also more difficult to fly.

The " direct take-off " Autogiro clearly indicated another method by which a no-run take-off could be achieved. As a means to an end it was a step in the right direction, and its development to a practical stage was

Fig. 1. *First successful Autogiro* 1923

a triumph of engineering ingenuity. Nevertheless it was an inelegant way of achieving a desirable objective; for transition from the static to airborne condition was too abrupt. The alternative method of the " towering take-off " demonstrated by the Hafner gyroplane also provided an acceptable interim solution to this particular problem.

But the real key to the optimum in ultra slow speed flying performance is undoubtedly the ability to hover in still air; and it is undisputable that the helicopter has fairly, and adequately, bridged that last remaining and all important gap in the slow speed range. That gentle levitation clear of the ground; the effortless pause motionless in space; and the thistledown-like landing on one's own shadow is slow motion flying in its purest and most elegant form; the practical attainment of which will always be associated with the name of IGOR SIKORSKY.

In attaining this optimum at one end of the performance scale, however, a penalty has had to be paid at the other, for no helicopter so far devised can be landed without power with the facility normal to the Autogiro. The manœuvres associated with an autorotational descent and landing at present call for an unusually high degree of skill in pilotage, and a consequentially unnecessary hazard to the aircraft is involved unless, and until, the disc loading can be reduced to a more reasonable value.

The too rapid loss in height resulting from this high disc loading is mainly due to the mechanical complexity, and extra structural weight involved in applying continuous power to the rotor system. It is the major part of the penalty that so far has had to be paid for the privilege of hovering. Now that the basic principles governing flight at zero speed have been established, more attention will undoubtedly be given to this problem of excessive weight; for any improvement cannot do other than

result in corresponding beneficial advantages in other performance characteristics.

Nevertheless, and as a means of indicating that refinements in detail design do not necessarily lead to that desirable reduction in structural weight which I am convinced is the most direct, logical and advantageous

Fig. 2. C.19 Mk.IV Autogiro, 1932.

approach to improved all-round performance, I propose to present some data based on the past, the lessons of which may be of assistance in the future.

In this analysis I have selected four different types of Autogiro, and one helicopter. The basis for comparative purposes is that all are, or were, in the two-seater category; all were produced in reasonable numbers; and each incorporated some essential refinement to enhance the performance of its predecessor.

	Autogiros				Helicopter
Refinement	C.19. Mk.III	C.19. Mk. IV Clutch	C.30 Direct control	C.40 Direct take-off	R-4 Hovering
Empty Weight (lb.) ...	935	1057	1269	1350	2011
All-Up Weight (lb.)...	1400	1550	1900	1950	2540
Power	100	100	140	175	200
Rotor Diam. (Ft.) ...	35	34	37	40	38
No. of Blades ...	4	3	3	3	3
Disc Loading (lb./s.ft.)	1.5	1.7	1.76	1.5	2.24
Power Loading (lb./h.p.)	14	15.5	13.6	11.1	12.7

The first is the C.19 Mk. III Autogiro of the 1930 period. With a weight empty of 935 lbs., and an all up weight of 1,400 lbs., this machine had a four-bladed rotor; blade interbracing and suspension cables; stub wings with ailerons; a biplane type tail with elevators and rudders; and an

Fig. 3. *C.*40 *" direct take-off " Autogiro.* 1939.

engine of 100 h.p. This aircraft had the unusually low disc loading of 1.5 lb./sq. ft. but a high power loading of 14 lb./h.p.

The next selection is the C.19 Mark IV Autogiro. Although the conventional aeroplane type controls and the same power plant as in the Mk. III were retained; the main rotor now had only three blades, and the tail was of conventional appearance. The essential refinement in this case was the installation of a clutch to simplify the take-off technique which hitherto had been somewhat cumbersome. Nevertheless, despite the obvious clean-up in external appearance the empty weight had increased by 122 lbs. The all-up weight was correspondingly increased also by the round figure of 150 lbs.; the disc loading went up from 1.5 to 1.7 lb./sq. ft., and the power loading from 14 to 15.5 lb./h.p. Note particularly that the equivalent of an extra passenger was already showing itself in the shape of increased structural weight.

The third example is the well-known C.30 " direct control " type of Autogiro. Here the stub wings and all normal control surfaces have been dispensed with. The flying controls were reduced in number to the barest minimum of two—just a hanging stick type of control column and a throttle. But the empty weight had now jumped another 212 lbs.—well over the equivalent of another passenger—and the all-up weight by no less than 350 lbs. Although the rotor diameter was increased by 3 ft., the disc loading rose to 1.76 lb./sq. ft. Note also the necessity for an increase of 40 h.p. from the engine to keep the power/weight ratio within reasonable limits which, at 13.6 lb./h.p. was an improvement on the previous type. Here the essential refinement in design was a form of control the efficiency of which was quite independent of translational speed. From the general performance point of view there was no improvement on the previous type.

The fourth type is the C.40 " direct take-off " Autogiro. The penalty of undue structural weight on performance had by now become more fully appreciated, for despite a further increase of 3 ft. in the rotor diameter, and a more mechanically complicated rotor hub and transmissional system,

the empty weight increased by only 81 lbs., and the all-up weight by a modest 50 lbs. There was a marked improvement in the disc loading at 1.5 lb./sq. ft.; and, resulting from an increase of 35 h.p. in the power requirement, the power loading was also reduced to the more reasonable value of 11.1 lb./h.p. This particular Autogiro was the direct forerunner of the single rotor helicopter, for the essential refinement in design enabled it with full load to make a no-run take-off in still air. As stated previously, this particular method of take-off had not the elegancy of the seemingly effortless take-off normal to the helicopter; but as a means to an end it was effective.

Finally, we come to the first practical type of single rotor helicopter, the well-known and familiar Sikorsky R.-4. The essential refinement in design is of course the continuous application of power to the main rotor, and the addition of a tail rotor; the combination providing the ability to hover, and a hitherto unusual degree of slow speed manœuvrability about all axes. But the price paid in additional structural weight at 661 lbs. has been a heavy one; the power loading, despite an extra 35 h.p., has increased to 12.7 lb./h.p.; and, worst feature of all, the disc loading has now gone up to the unduly high value of 2.24 lb./sq. ft., which, translated into more practical terms implies a power-off vertical rate of descent with full load in still air of 40ft./sec., or about 27 m.p.h.

A summarization of the foregoing analysis indicates that the ability to hover has thus far proved to be an expensive luxury. Expressed again in practical terms, the Sikorsky R.-4 helicopter by direct comparison with the C.40 Autogiro is actually carrying in the shape of added structural weight the equivalent of almost four extra passengers; or alternatively an additional six passengers by comparison with the earliest practical C.19 Mk. IV Autogiro. Expressing this in another way, the helicopter as we know it is roughly 1,000 lbs. heavier than the comparable gyroplane, and requires twice the power, with no corresponding improvement in the useful load, high speed, rate of climb, or basic landing performance characteristics.

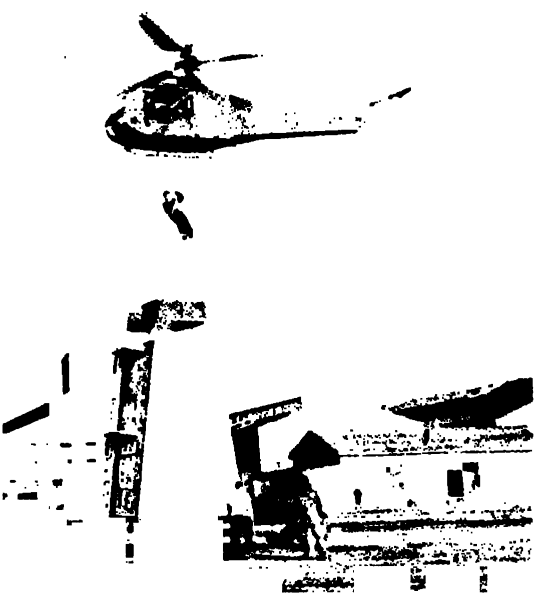

Fig. 4. Sikorsky R-4 helicopter —less conventional undercarriage— hovers well clear of ground cushion effect.

I particularly stress this structural weight aspect because I know only too well from past practical experience its influence on power and disc loading, and the undesirable effect it has on performance generally.

At the week-end meetings which used to be a feature of pre-war flying activities it was occasionally necessary to do a certain amount of juggling with removable equipment prior to staging a special demonstration, and I recall quite vividly how the removal of just one gallon of oil—the equivalent of only ten pounds in weight—from the tank of a C.30 used to make a remarkable difference to the take-off, slow flying and landing characteristics. When thus flying extra light one seemed to strike an optimum value in performance, for the aircraft was certainly much more lively to handle, with an appreciable improvement in response to a given control movement.

Thus it might well be asked whether, in fact, the development of this particular and inherent hovering characteristic of the helicopter has been worth while. To that there can be only one very positive answer, for the ability to operate a mechanical contrivance directly from or above any kind of terrain, whether it be land, water, snow, ice, or even the stickiest mud, opens up a vast and hitherto untapped field of usage. For centuries mankind has been waiting expectantly for such a miracle to happen, the potentialities of which are such as to stagger the imagination.

But the helicopter is nothing more or less than another means of transport. Its main purpose is one of convenience; to save time; and if it is to take its rightful place with other and more normally accepted means it must be able to operate with facility and safety. Additionally, of course, it must be able also to operate economically, but that particular aspect is not of immediate importance.

So in considering the problems associated with any particular form of helicopter operation, it is essential from the outset, if the objective is to have any practical value, that certain basic features of design should conform to certain definite minimum standards of requirement.

First and foremost, therefore, I consider that the most important requirement governing the basic features of design applicable to any type of helicopter intended for practical operation, is that the take-off and landing must be accomplished with greater facility, and the exercise of less skill than is possible at present. Whilst any take-off is entirely optional, the same cannot be said about any landing. Consequently I attach particular importance to the power-off autorotational characteristics, and thus to the value of disc loading, which for any given diameter of rotor is roughly proportional to the weight carried. The most direct method of reducing the disc loading to a reasonable value is by the simple expedient of getting rid of much of that excess structural weight, the extent of which I have already indicated. On this particular activity, there is undoubtedly considerable scope for ingenuity on the part of engineers who are specialists in weight control; for there is no denying that in the past there have been glaring discrepancies between design estimates and those actually achieved in practice.

So I would say, "Look after the disc loading, and the power loading will look after itself." With the amount of practical knowledge and experience now available surely it is reasonable to expect that under full load

conditions, the values of power and disc loading on the helicopters of to-morrow should not exceed ten and two respectively. On the other hand, if I were asked what I considered a desirable target to aim for in regard to disc loading, I would unhesitatingly reply 1.5 lb./sq.ft.

The rotor configuration employed on any particular type of helicopter is, or should be, largely influenced by general performance requirements, and in the present state of the art the designer appears to have many alternatives at his disposal. But there are traps for the unwary, for the apparently simple theoretical layout may prove to be quite impracticable.

I suggest, however, that as long as it can be made to suffice, the employment of a single main rotor is preferable to that of a multiple system, if only from the point of view that it is a known quantity; is more simple mechanically; and easier to maintain. Although a tail rotor may offend the æsthetic taste, it is a most efficient and practical means of correcting torque, and provides a quality of control in the yawing plane for which it may prove difficult to devise a more efficient substitute.

Now almost an antique, the Sikorsky R-4 is still the only practical type of helicopter in daily use in this country. Although somewhat tricky to handle, its use in many parts of the world has been instrumental in providing a most valuable source of knowledge, and experience, of an extremely varied nature. As a result it seems likely that certain essential refinements in detail design will be an important feature of all new prototype construction of the immediate future. Consequently I propose to make only a brief reference to certain features of design, which are a matter of common interest to all concerned with helicopter operation.

From the control point of view, the principal handicap hitherto has been the necessity for manual adjustment and synchronization of collective pitch and throttle during flight; and the manual reduction of pitch in the event of engine failure. This has now been successfully overcome by purely automatic means. Whether it is preferable to use a normal throttle lever, or the more conventional helicopter collective pitch lever as an altitude control is a question for which only the actual user can provide an adequate answer. Personally, I believe that the proposed use of the main pitch lever as a means of reducing rate of descent during a genuine forced landing will be found in practice to call for such an unusual degree of timing and precision as to make the desired result somewhat difficult of achievement. For that reason I would prefer that the pitch of the main rotor should be governor controlled, and that control of the engine should be by means of a conventional throttle. Better still, I would prefer that there should be no necessity ever to have to worry about the pitch of the main rotor; that it should always be well within the autorotative range.

Pilot fatigue, especially on cross-country flights, is accentuated by residual off-set loads in the control column. These loads arise from a displacement of the C.G. of the aircraft, and their suppression by means of some simple and easily operated form of mechanical bias is most desirable.

For a considerable time I have felt that the push-pull, split wheel type of dashboard mounted control column is particularly well suited to rotor systems, and that experimentation with such an installation would be a most useful form of research activity. With the incorporation of suitable

friction means to locate the fore and aft position of the rod, as well as the lateral position of the wheel, it should be possible, with correct adjustment, to fly hands-off with facility and precision.

Although I do not believe it to be an essential immediate requirement that helicopters *must* be able to fly on instruments alone, I believe it to be a matter of importance that they *should* be able to do so. There is

Fig. 5. Sikorsky R-5 equipped with pontoons.

no doubt at all about the actual efficiency of present control systems, but there is considerable room for refinement in design, and I feel the optimum will not have been reached until one can fly blind with facility.

Whilst from the control point of view the number of blades per rotor is immaterial, there are of course certain aspects of rotor blade design which have a most important influence on helicopter operation. It is not my intention to endeavour to elucidate those various parameters which form the basic features of design, for that particular field of specialist activity is the strict preserve of the aerodynamicist and the engineer. Suffice it to say that the basic requirements governing the employment of any particular rotor configuration are that it shall remain attached to the aircraft; that it shall continue to rotate during all conditions of flight; and that it shall be free from excessive vibrations.

Whether the individual blades shall be constructed of metal and wood (which is the most highly developed form of assembly to date), or alternatively whether they shall be all-wood or all-metal is not a matter about which one should attempt to be dogmatic. From the design point of view there is much to be said for all three methods. What is of major concern, however, is the behaviour in flight of the finished product, for here the operator, the maintenance engineer and the pilot all have a vital interest.

Ease and cheapness of production; regularity of aerodynamic contour; smoothness of profile finish; standardization of unit weight; and resistance to damage, are all essential features of good blade construction.

Cheapness of production is of concern to the operator because the purchase price of the finished assembly, and expenditure on replacements, has a direct bearing on operating costs.

Standardization of unit weight, and resistance to damage, affects both the operator and aircraft engineer in that it allows an appreciable reduction in the number of spares which must be carried; and considerably reduces, in fact, it might altogether eliminate, a lot of wasteful effort and time spent in balancing and matching rotor blades.

Resistance to damage particularly includes the abrasive effects of heavy rain or hail on the leading edges, the repair of which also involves many hours of maintenance work, and much needless expense.

The regularity of aerodynamic shape, and smoothness of profile, are matters of direct concern to the pilot who is vitally interested in the absence of undue vibration, and the propulsive efficiency of the rotor system.

Theoretically the all-metal type of blade construction would appear to be the ultimate answer, although I have no doubt that the protagonists

Fig. 6. Sikorsky R-5 demonstrates its ability to lift an overload.

of the laminated compressed wood school of thought can produce very convincing evidence against such a suggestion. A considerable amount of parallel research on both methods is currently taking place, and the decision as to which is the best method must be left to time, and the user.

Ease of rotor storage is another matter of operational importance likely

to call for much ingenuity in design. The question here involves reducing the overall dimensions of the aircraft for hangarage, or other reasons. Should the blades be capable of folding over the tail; or should a master blade be located aft of the pylon, and the remaining blades be removed and stored along the fuselage ? Folding has the advantage of reducing the possibility of damage in handling; but how, especially on bigger types of helicopters, is folding going to be accomplished except by mechanical means ? That in turn means more mechanical complication and additional weight. On the other hand exactly how are blades to be removed, and reassembled, without the aid of specially devised lifting equipment ?

Of course it may conceivably follow that this particular problem will only arise with the lighter types of personal helicopter with which roadability will undoubtedly be a major feature of design and utility at some future date; and that in general it will be normal for transport type helicopters to remain parked in the open with rotors extended, except for purposes of major overhaul.

Even so, however, some means will be essential to prevent undue stresses at the root end, and damage to the blades resulting from undesirable motion about the flapping hinges, due to wind action. The present normal method of restraint is by means of flexible covers on the blade tips. But the rotor hubs of bigger helicopters are likely to be at such a height above ground level as to make the blade tips unreachable other than by some kind of portable ladder, which might not be readily available when particularly required.

A possible answer to this problem might be some form of retractable anchorage eye mounted internally of the blade and towards the tip, which can be caused to retract automatically during flight, and is only open when the rotor r.p.m. fall below a certain predetermined value. The only piece of removable equipment which would then be required would be a hooked rod with a length of cord attached for connection to some convenient part of the undercarriage or fuselage.

Fig. 7. Sikorsky R-4 in hovering flight. Mr. Igor Sikorsky converses with crew.

Association of Gt. Britain.

Precisely the same problem of blade restraint under comparable conditions will arise with any form of rigid rotor system, if ever one proves to be practical; although, as any rigidly mounted form of cantilever blade is in fact flexible in the flapping plane, it is more correct to refer to such a system as "hingeless".

Having discussed certain features of design common to helicopters in general, the influence of which have an important effect on the operation of the aircraft, let us now consider the problem of actual helicopter operation, and the influence it is likely to have on design.

The benefit of practical knowledge gained from past operational experience is already considerable. Although mainly of a Service nature, this knowledge is equally valuable and applicable to civil activities. In fact, it is quite evident that the basic dividing line between Service and civil requirements, and its influence on design, is a fine one. Any form of difficult or normally inconvenient short distance communication; rescue in its many guises; pest control by dusting or spraying; the carriage of mails; geological surveys and oblique photography, are but a few of the many obvious examples of duties for which the helicopter is particularly well suited. So much so, in fact, that there appears to be no definable limit to the potentialities which lie ahead.

The necessity for the helicopter arises from the universal realisation that there exists a gap in the facilities provided by existing means of communication. The aeroplane suffers from the limitation of requiring specially prepared areas of considerable size to permit it to take-off and land with reasonable facility. In consequence, and to justify its use from an economic standpoint, it is forced to operate between fixed and widely separated terminal points. On the other hand, and although able to operate over routes of extremely short distances, the train and the omnibus is also equally dependent on specially prepared tracks or roads, the limitation of which have only become apparent with the ever growing realisation of the advantages arising from the use of the air as a means of saving time.

Fig. 8. Deck landing experiments on British merchant ship "Daghestan." In foreground is experimental version of Brie patent landing and launching platform. U.S. waters, 1943.

The primary function of the helicopter therefore is to forge the missing link which will bridge that obvious gap in the facilities for travel at our disposal, by providing a degree of flexibility hitherto unattainable with any other means of transport. It should therefore be considered as a valuable adjunct to the aeroplane, the train, the bus, and incidentally to certain nautical activities ; for at this particular stage in its development it would be unwise to attempt to employ it in any directly competitive manner. Only as and when convincing proof is forthcoming of the helicopter's ability to render superior service should it be considered as a replacement of existing means.

To have any worthwhile utility value therefore, the helicopter must be able to provide, and carry out, some essential public service in a convenient and acceptable manner. It must be able to save time and effort. Further, it must be able to do so economically. With that object in view it must be able profitably to carry a reasonable pay load ; whether in the form of passengers or cargo depending on the nature of its employment.

Despite the limitations at present imposed by excessive structural weight on the load which a helicopter can carry for a given power, convincing proof is already to hand of its possibilities as a weight lifter under favourable conditions. By way of illustration here is a slide of the Sikorsky R-5 type (which for military purposes was originally designed as a two seater), airborne with sixteen passengers ; in actual weight the equivalent of a ton, or double its normal useful load. (Fig. 6.)

Obviously one cannot carry fare paying passengers about in such an exposed manner, but does it not appear possible that with some suitable rearrangement of the shape of the fuselage at least half that number could be carried conveniently on a journey, the duration of which might be only a matter of a few minutes? The helicopter itself is still somewhat unconventional, and thus provides a suitable motive for treating the peculiar problems of design associated with its employment in an unconventional manner.

Alternatively, and when used as an aerial crane for transporting bulky loads over short distances at low speed, where is the necessity to think in terms of streamlining, internal stowage, or even a fuselage in the accepted sense at all? A bulldozer is none the less efficient because it bears little resemblance to a lorry!

Another feature of design worthy of serious consideration relates to the undercarriage structure. Do we need conventional aeroplane type wheels and brakes on an aircraft which normally takes off and lands without any forward run, and with which even taxying is an exceptional and unnecessary manœuvre? Further, what is the necessity for massive and weight consuming shock absorbing struts? If it is considered imperative to provide some additional safeguards to accommodate the impact loads following an autorotational landing in the event of power failure, may it not be possible to devise some alternative and lighter arrangement in lieu?

One of the unique operational features of the helicopter is associated with its amazing amphibious characteristics, and this independence of terrain so enhances its general utility value as to focus attention on the provision of suitable means for providing buoyancy. To date the use of

low pressure air inflated rubber type pontoons has proved very satisfactory, but it is suggested that here is another instance where the versatility of the helicopter stimulates thoughtful investigation, and the exercise of ingenuity on the part of designers, into the possibility of evolving a lighter and more elegant means of amphibious structure.

With shipboard operation involving flights over the open sea, pontoons or floats would obviously be impracticable for landing in rough water, although in any case some form of floatation gear must be provided for the crew. Even wheels would serve no useful purpose on the flight deck area owing to limitations of space. Hence this is an instance of special application where the conventional undercarriage might be entirely dispensed with, and the corresponding weight saved put to some more useful purpose. (Fig. 4.)

The helicopter has the ability to make any vessel with sufficient space to accommodate it an independent aircraft carrier, and experience to date has indicated that an aft location is most suitable for flight operation. When such a vessel—a cruiser or merchant ship for instance—is subject to any pronounced rolling or pitching movement, the small specially provided flight deck area is subject to an appreciable lateral and vertical displacement which can best be described as a kind of corkscrew wallowing motion. This instability, however, is of a non-periodic order, and during the few seconds available when at its minimum, a take-off or landing present no undue difficulties. A major problem with such operation is associated with providing adequate means to restrain the aircraft on the deck during the period of maximum instability, and yet enable it to take-off and land with facility whenever so desired. Manhandling under such conditions is not only dangerous but impracticable, and the ideal solution must be such as to allow the pilot to carry out all essential manœuvres of his own accord.

To this end the aircraft might be mounted on a platform of small area (say roughly half that of the rotor disc area), which is capable of being oriented into the resultant wind, thus obviating any necessity for a change in the ship's heading. (Fig. 8.) The platform itself could consist of a hollow rectangular frame within which are located a number of equally spaced flexibly tensioned cables, on which the aircraft is mounted and anchored by means of suitable hooks fitted to the lower sides of the fuselage. These hooks would be self-locking on making contact with the supporting cables, thus automatically anchoring the aircraft, and relieving the pilot of any anxiety about its stability or safety. For the take-off, and at the pilot's discretion, the hooks would be released by means of an auxiliary control.

It is conceivable that some such form of landing and take-off platform might also prove of practical use for normal commercial helicopter operation from a fixed base on land, for this conception of an undercarriageless aircraft appears to offer a positive and simple method of saving unnecessary structural weight, thus providing the means for an appreciable increase in useful load carrying capacity.

At this particular stage in the development of the rotary wing art it would be a matter of pure conjecture to attempt to predict exactly how

helicopters will ultimately be used for carrying fare paying passengers; the nature of the routes on which they will be operated; or the minimum capacity which will prove economically acceptable to operators.

Let us be content therefore to leave the distant future to itself, and think in the more positive terms of the present and immediate future. In the Sikorsky S-51 type which is now being produced and operated in America, and models of which possibly will be in use over here later this year, we have adequate proof of the existence of a practical type of helicopter with immediate commercial possibilities. (Fig. 9.)

To many people, some of whom are not too well disposed towards the unconventional, the idea of giving serious consideration to an aircraft with a cruising speed of only 80 m.p.m. appears somewhat ridiculous, so it appears worth while recalling that the aeroplanes used on the first commercial services operated in this country, and elsewhere in 1920, had a similar cruising performance.

Now, however, it is not the intention to operate between one country and another, or over what in those somewhat distant days were comparatively long distance routes of 250 miles or so: but rather to take advantage of the inherent limitations of the aeroplane by operating on those time consuming short distance journeys between terminal airport and city centre: between one populated area and another; and between one county and another.

For speed as such is relative, and quite meaningless in the field of air transportation unless it can be employed and used advantageously. It is not the maximum speed, but the average speed at which a journey is accomplished which matters. With helicopter operation there is no necessity to think in terms of miles an hour as such; but rather to plan in terms of elapsed time. In other words, how long will it take to get from the point of departure to point of arrival?

It will suffice to mention that over a distance of 150 miles under still air conditions, a helicopter cruising at 80 m.p.h. and capable of operating from the centre of one city to another, is relatively as fast as an aeroplane cruising at twice that speed. Not only has the tedious road journey to and from the airport been eliminated, but from the passengers point of view there is the added convenience of avoiding an unnecessary change from one vehicle to another.

With the example given, however, there is of course no advantageous saving in time as between one method and another, so one could assume that at present it would be advisable in the case of helicopters employed on scheduled route services to limit the maximum range to a distance of 100 miles.

At the other end of the distance scale there is the fairly obvious feeder route of ten to fifteen miles between terminal airport and city centre. In effect this would amount to a special charter service for the convenience of airline passengers, and the frequency of service would depend to a great extent on the aeroplane arrivals and departures at the airport being served.

It may well be that many passengers arriving at Heathrow for instance might not necessarily desire to enter London at all, but would prefer to travel direct to their ultimate destination which still might be only a few

miles distant. This kind of service would open up an entirely new field in airport traffic dispersal, in which the airport itself would be the hub, and the helicopter services would radiate to all points of the compass like the spokes of a wheel.

On the other hand, and despite the ability of the helicopter to operate from practically any small open space, it would be illogical to expect that in actual practice it will be allowed to do so indiscriminately. Owners of property and the public in general have their rights, and it appears reasonable to anticipate that in the course of time there will have to be provided carefully selected, and possibly licensed areas for helicopter operation.

The precise solution to this and many more such pertinent problems will only become apparent through practical trial and error methods; but as operation to and from the centres of towns and cities with their densely populated areas, may possibly be one of the main objectives of scheduled or unscheduled helicopter services involving the carrying of passengers and mail, there are certain other factors which also call for serious consideration.

For instance, all civil flying activities are governed by the Air Navigation Regulations, and the question might well be asked as to how helicopters can land and take-off from the centre of London for example, if one of the main provisions of these Regulations is that no aircraft may fly over a populated or built-up area except at such a height that in the event of power failure it can glide to the outskirts to land?

The object of this provision of course is for the protection of the interest of persons and property on the ground, and whilst its application in so far as helicopters are concerned might at first sight appear to be unduly restrictive, there is no doubt at all but that at this particular stage of development it would be as well to keep it in force. However optimistic

Fig. 9. The Sikorsky S.51.

we may be about this new method of travel, let us not be blind to its limitations. Although it is common knowledge that a helicopter can land in a very restricted space, it is not so generally appreciated that the minimum area considered necessary for normal operation where obstructions are present, is of the order of 100 yards square. For such a convenient parking place to be readily available for an emergency landing in the event of power failure for instance, would be nothing more or less than sheer luck. To gamble on such an improbability would be the height of folly, and it is for that reason alone, that the employment of any single-engined helicopter for any purpose in a built-up area, calls for the most careful consideration before being permitted.

I am not opposed to roof top operation as such, for such appears inevitable at some future date; in fact the upper structure of existing terminal railway stations appears to be particularly well suited, both as to size and location, for this particular purpose. But as a precautionary measure, an essential preliminary feature of aircraft design should be the installation of two power units, so that height can be maintained on one in the event of partial power failure.

Nevertheless, there is urgent necessity for an intensive period of practical experimentation of a day-to-day nature, to enable factual data to be obtained as to the extent of the need for inter-city services; in what manner they should be operated: the type and size of helicopter best suited for this specialized purpose: and where the terminal centres are to be located.

In the meantime therefore, it is suggested that this valuable and essential information can readily be obtained with a single engined helicopter, and the use of the river Thames. Not only does this river flow through the centre of London, but it also provides an easily identifiable route from above, which can be followed with facility, even under conditions of extremely poor visibility; in fact flying need only cease when the tops of bridges were obscured. As a temporary expedient a moored flat topped barge in the Westminster or Blackfriars area would suffice for the central city terminal; incoming aircraft being confined to one bank of the river, and outgoing to the other. For later commercial operation the barge could be replaced by small specially designed platforms sited at frequent intervals along either bank; the number and location of which would naturally be dictated by experience. As a precautionary measure against the possibility of a forced landing, which would deliberately be made on the river, the aircraft would be equipped with pontoons, and some form of light anchor to guard against tidal flow.

It was as long ago as 1934 that I first conceived and officially proposed this "Riverdrome" scheme and, with the exception that it is now proposed to use helicopters instead of Autogiros, I believe that conception today to be as logical an approach to a pressing problem as it was then.

As a means to an end this scheme has the essential practical qualities of simplicity, low cost and maximum safety. For it to be tried out, some relaxation of the Air Navigation Regulations is still necessary; but I submit the use of the river does provide a reasonable loophole for special dispensation by the controlling authority.

Another feature of design which will undoubtably call for attention wherever frequent low altitude flying over populated areas is involved, is an appreciable reduction in the noise level from the engine. This probably would involve the addition of a little extra weight, but its effect on performance should be negligible, at what amounts to sea level operation.

I have already referred to the proven capacity of the helicopter as a weight lifter, and for certain requirements there seems to be no reason why any well designed helicopter should not be capable of lifting its own weight in the form of useful load. In order to take advantage of all the possiblities that the helicopter has to offer it is necessary to divorce one's mind and its associated ideas, from what might be termed " the fixed wing complex." For the time being at any rate, the helicopter is a short haul vehicle. As such its endurance, and thus the quantity of petrol it must carry need be expressed in terms of minutes only. If this assumption is correct, here is another method by which the pay load might be increased. Where and how are the additional passengers thus made possible to be accommodated under a single rotor? And in what manner will the resultant stability and trim problems be met?

It is also pertinent to enquire whether passenger seats are really necessary on such short distance journeys, or whether in fact the valuable space normally taken up by such revenüe eating fittings might not be more advantageously utilized for the mutual benefit of the " aerial strap-hanger "; and operator? If course I do not expect such an unorthodox suggestion to be immediately accepted in certain quarters with the seriousness it deserves, if only on account of the fact that in this country it has not yet been possible to reproduce or even demonstrate, the vast strides being made elsewhere.

A fortunate and most agreeable characteristic of rotary wing flight, and one which all passengers will be quick to appreciate, is the apparent immunity of the aircraft from the disturbing and unpleasant effects occasioned by gusty air conditions. The rotor is in effect an efficient aerodynamic shock absorber, which absorbs and dissipates those sudden jolts, which normally cause personal discomfort, before they reach the fuselage.

Fig. 10. *A typical example of an unstable platform. To facilitate shipboard operation, positive anchorage of the helicopter to the deck is essential.*

If my conception of the future possibilities of helicopter travel, is as well-founded as I believe it to be, there is equally good reason to be optimistic also about developments generally in the aircraft itself, for it seems possible that the twenty and thirty passenger helicopter might be much nearer to practical fulfilment than hitherto suspected.

With the cumulative knowledge and experience now available, an intensive and accelerated programme of short-term research into the possibilities of bigger, and more efficient rotor blades might be productive of rather suprising results. It is my firm belief that only the fringe of what we may ultimately achieve with a single rotor system has as yet been touched, and I would like to see a rather more concentrated effort devoted at this stage to the engineering problems involved in the development of a 60ft. diameter rotor, rather than to multiple rotor systems of smaller diameter, but greater mechanical complexity.

To go from one extreme to the other, a rather extraordinary feature of current activity in this country is the neglect of the private owner's requirements. The reason for this apparent indifference to the sales potentialities of the personal type of helicopter is somewhat difficult to understand, for one would have thought it a comparatively simple and straightforward matter to construct a small machine capable of carrying one or two persons. Exactly when and in what matter this situation will change is problematical, but my own opinion is that the automobile industry, with its highly developed engineering methods of production, is in an excellent position to participate in the potentialities of this alternative, and most promising method of transport, whenever it chooses.

Earlier in my lecture I referred to the relative performance characteristics of the Autogiro and the helicopter, and the penalty so far paid in the achievement of hovering flight. Quite apart from the immediate necessity to tackle the problem of a reduction in structural weight, it appears likely that that desirable improvement in all-round efficiency and performance may come about through some bright new idea for achieving vertical flight without the necessity for the present complicated transmission system. The torqueless rotor which is always functioning well within the autorotative pitch range is obviously the basis of approach, but whether the rotative means for take-off and landing will be by jets, rockets, or some other at present obscure method, must be left for the future to decide.

Shorn of its technicalities, the helicopter is nothing more or less than a very precise and highly ingenious example of mechanical engineering. In discussing its limitations, and the associated problems of operation and design I have endevoured to be tolerantly critical, but constructively so. Above all I have tried to be realistic and provocative, and I thank you for coming here this afternoon to listen to me.

Limitations in Helicopter Design

By J. A. J. BENNETT, D.Sc., F.R.Ae.S.

A Lecture presented to the Helicopter Association of Gt. Britain, 22nd Feb., 1947, at Manson House, 26, Portland Place, London, W.1.

H. A. MARSH, A.F.C., A.F.R.Ae.S., IN THE CHAIR.

INTRODUCTION BY THE CHAIRMAN

Ladies and Gentlemen,

As most of you know this is the Fourth and last lecture of our present session, the other three having been given by Gp/Capt. LIPTROT, Mr. C. G. PULLIN and Mr. R. A. C. BRIE, covering an historical survey, design and operation of helicopters, etc., and to-day our lecturer is discussing "Limitations in Helicopter Design."

It gives me very great pleasure to introduce Dr. BENNETT to you, for I have known him personally for fifteen years or more, during the whole of which time he has been intimately associated with rotary wing and helicopter design.

For some years prior to the war, Dr. BENNETT was with Messrs. G. & J. Weir and the Cierva Autogiro Co.; and during the war was C.T.O. at the Airborne Forces Experimental Establishment and spent two years in the U.S.A. where he latterly was attached to Wright Field as project engineer on helicopter research. He is at present head of the Helicopter Branch of the Fairey Aviation Co. Ltd., and besides his many academical qualifications he is a F.R.Ae.S., a Founder Member and a Member of the Council of our Association, a Member of the Helicopter Committee of the Aeronautical Research Council and a Member and past Vice-President of the Helicopter Society of America.

It can be readily seen that he is eminently suited to talk to us on the subject he has chosen.

On behalf of the Association it gives me great pleasure to welcome our guests this afternoon, who I feel sure will be well rewarded for coming along.

DR. J. A. J. BENNETT

MR. CHAIRMAN, Members of the Helicopter Association and Guests, I regret that I have chosen as the subject of my talk: "Limitations in Helicopter Design." I think that a more appropriate title for this afternoon would have been: "Limitations in Design for Living." However, we have already heard enough about that from the Ministry of Fuel and I shall endeavour to confine my further remarks to the subject of helicopters. I should like to say first of all how gratifying it is, to those of us who were concerned with rotary wing development before the War, to witness, in the immediate post-war period, a general acceptance of the helicopter as a practical aircraft, and a widespread enthusiasm for its unique characteristics. There is no longer any doubt about the future possibilities of the helicopter, thanks to the intensive work of IGOR SIKORSKY and his colleague MICHAEL GLUHAREFF, under the direction of whom the helicopter first became a fully-fledged flying machine.

In spite of this historic achievement and the subsequent production of military helicopters in the United States, I believe that we still have a long way to go in the investigation of the basic problems of rotary wing flight. Fortunately, due to the work of JUAN DE LA CIERVA and those who had the foresight to sponsor his experiments, there is available a background of rotary wing experience that helps in the appreciation of the inherent limitations which have impeded, and continue to impede, progress in helicopter development. I propose this afternoon to discuss briefly some of these limitations in the course of a general review of the present technical position.

The hinged rotor blade

Probably no other single feature contributed more towards the achievement of practical rotary wing flight than did the flapping hinge. Although it had been described in early helicopter patents as a means for suppressing vertical bending at the root of each blade, it became of primary importance for single rotor aircraft in balancing the dissymmetry of lift in forward flight (Fig. 1), which with rigidly-mounted blades caused a rolling couple of increasing magnitude as the forward speed increased. In the words of the main claim of the original Autogiro patent, the intention was that the

rotating wing (Fig. 2) should adopt at every instant the position required for equilibrium between the centrifugal force produced by the speed of rotation and the lift due to the action of the wind on the wing. This intention was frustrated, however, by the inertia of the blade.

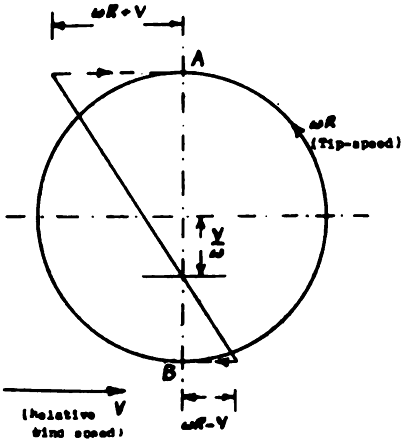

Fig. 1. Dissymmetry in forward flight.

Inertia imposes a natural oscillation (like that of a pendulum) on the motion of the blade about the flapping hinge, thereby preventing a condition of equilibrium between centrifugal force and lift. If the angle of the blade about the flapping hinge in any azimuth be denoted by x and the rotor

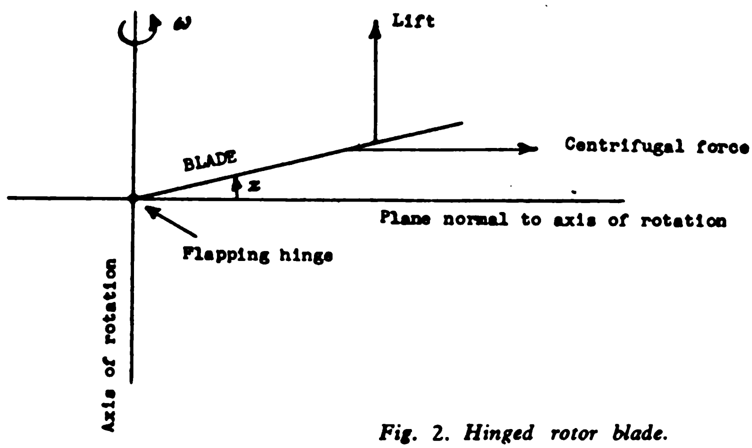

Fig. 2. Hinged rotor blade.

angular speed by w, the equation of motion of the free undamped oscillations is $x + w^2x = 0$ which is identical with that of a simple pendulum of frequency w. Hence the natural frequency in flapping is equal to the speed of rotation.

Now the periodic disturbing force due to the dissymmetry of forward flight has the same frequency and is, therefore, in resonance with the natural flapping oscillation of the blade. It is when resonance occurs in any mechanical vibration that there is a phase lag between the disturbing force and the

resulting displacement of exactly 90°. That is why, in a gyroplane, the flapping displacement of the blade is greatest after it has passed the nose of the machine although the position of maximum lift is on the advancing side of the rotor disc. Instead of the tip-path plane tilting laterally due to the dissymmetry of forward flight, it is tilted mainly longitudinally. Flapping, therefore, exchanges rolling of the aircraft for pitching. This phase lag between lift variation and flapping has been a basic limitation in rotary wing design, affecting adversely control response and, by inducing longitudinal dissymmetry in forward flight, affecting also stability, trim and rotor vibration.

The phase angle of 90° is unaffected by damping of the flapping motion so long as the ratio between the forced and natural frequencies $\frac{w}{w_n}$ is unity. This can be seen by reference to standard textbooks on the subject of vibration, where the amplitude of forced vibration and phase angle between force and displacement are shown (Fig. 3) as functions of

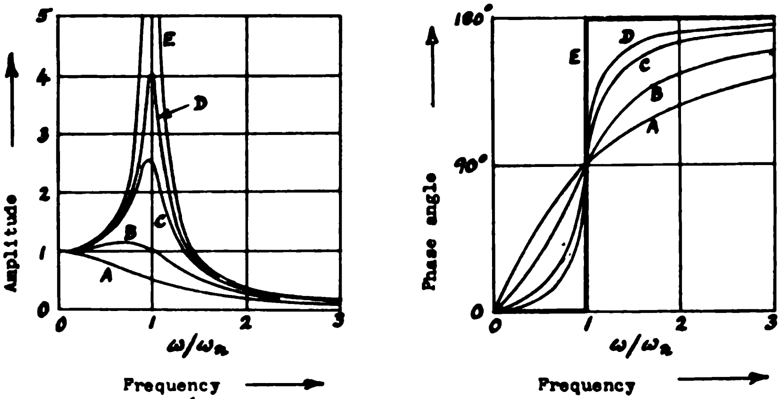

Fig. 3. Amplitude and phase angle of forced vibration

the frequency ratio for different values of damping. The equation of the damped free flapping motion is of the form:

$$I\ddot{x} + c\dot{x} + kx = 0$$

where the three terms represent respectively inertia, damping and restoring moments. The blade is, therefore, not merely in equilibrium between lift and centrifugal force but between these three moments. If the natural frequency were altered, for example, by locating the flapping hinge outboard from the axis of rotation or by inclining the flapping hinge in the plane of rotation or by restraining the motion elastically by means of a spring, the phase angle between the periodic disturbing force and flapping displacement would no longer be 90°, and it would be dependent also on damping.

Flapping, Hunting and Feathering

These three terms define the angular oscillation of the blade about three mutually perpendicular axes. Flapping is the angular oscillation of the blade about a pivot (the "flapping hinge") which allows the zenithal

angle of the blade to be varied ; hunting is the angular oscillation of the blade about a pivot (the "drag hinge") which allows the blade to be displaced angularly in azimuth with respect to the rotor head ; and feathering is the angular oscillation of the blade about a pivot (the "feathering hinge") which allows the blade angle to be varied.

We have seen how the flapping phase angle causes the tip-path plane to tilt longitudinally whenever there is lateral dissymmetry of lift, and of course to tilt laterally for any longitudinal dissymmetry of lift. The blade, therefore, rises and falls cyclically, thereby causing a variation in incidence

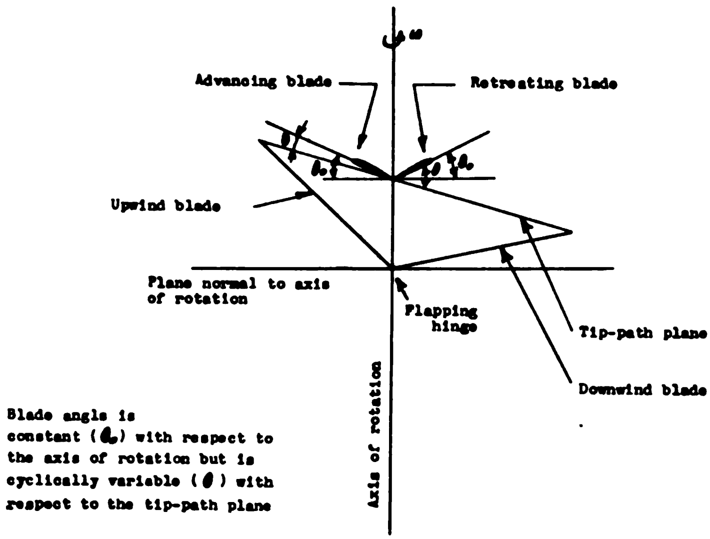

Fig. 4. Cyclic feathering with respect to the tip-path plane due to flapping.

with respect to the tip-path plane, i.e., cyclic feathering (Fig. 4). As flapping is merely a method of providing cyclic feathering of the blades with respect to the tip-path plane, feathering hinges can be used to do the same thing, in which case the tip-path plane need not be allowed to tilt but may remain at right angles to the axis of rotation.

The tilting of the tip-path plane causes a further dissymmetry (Fig. 5), viz. a cyclic force tending to oscillate the blades in azimuth. This force arises from the inertia of the blade and is known in rigid dynamics as the Coriolis force, because it was discovered by CORIOLIS more than a century ago as the component force normal to the path of a given mass moving in a rotating plane. Hence the necessity for a drag hinge, which relieves the blade root from the periodic bending moments which tend to promote blade failure by fatigue. However, the introduction of the drag hinge, giving each blade an additional degree of freedom of oscillation, has been responsible for rotor vibration troubles probably more than any other step in rotary wing development. The low natural frequency of one of the possible modes in which the blade may oscillate about the drag hinge is not very far removed from the frequency of the Coriolis forces, i.e., the angular

speed of the rotor, with the result that the hunting oscillation is unstable unless the freedom of movement of the blade about the drag hinge is is restricted by damping or by a spring restraint to increase the natural frequency of the hunting oscillation. Hunting instability manifests itself as a violent rocking of the aircraft during starting or stopping of the rotor on the ground under the additional restraint and damping of the under-carriage, and on take-off or landing with a forward run, and there have fortunately been very few occasions of such instability during flight. With

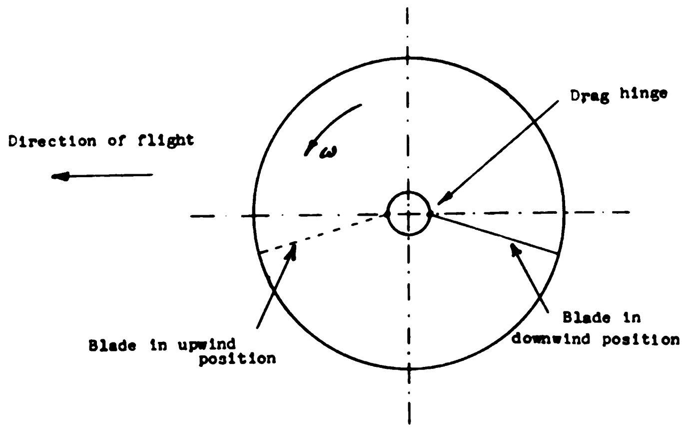

Fig. 5. "Hunting" oscillation of blade.

insufficient damping, the oscillations can increase in amplitude sufficiently to cause severe damage to the aircraft, and not the least perturbing feature of the instability is that it is self-excited. Hence the drag hinge, originally conceived as an assurance against blade fatigue, has become a potential instrument of self-destruction and, although it may be said to have successfully overcome one of the limitations of the flapping hinge, with which it forms a universal joint, it has achieved this result only at the expense of another limitation equally as critical as the first.

The Rigidly-mounted Blade.

Owing to the foregoing difficulties with hinged blades, investigations are currently in progress into alternative methods of balancing the dis-symmetry of lift in forward flight. In single rotor aircraft, the feathering hinge can effectively replace the flapping hinge for maintaining lateral trim, in which case the absence of Coriolis forces in steady flight renders the drag hinge unnecessary. With twin laterally-opposed rotors, lateral trim is, of course, no longer dependent on cyclic feathering, and the blades may be rigidly-mounted as in the orthodox propeller. That is not the end of flapping and feathering, however, or of hunting, because, even in the absence of a flapping hinge, the blade partially flaps owing to its own longitudinal flexibility. On the other hand, even in the absence of a feathering hinge, the blade partially feathers on account of periodic twist within the blade itself. The pitching moment of the aerofoil may be zero,

the blades may be designed to be straight for a given condition of flight, e.g., hovering, but the bending deflection at the blade tip in other conditions of flight combined with variation in torque causes internal feathering and there is also a pitching moment tending to diminish the blade angle owing to the leading edge of the aerofoil being at a greater coning angle than the trailing edge. This pitching moment obviously increases with blade angle and chord.

The rigidly-mounted blade is subject to periodic stress arising from:

(a) periodic variation of lift in forward flight;

(b) gyroscopic moments; and

(c) cyclic flap control (if blade flaps are provided instead of feathering hinges) including the longitudinal control necessary for trim at low airspeeds.

If rigidly-mounted blades could be built with sufficient structural strength to withstand the combination of periodic bending and the steady centrifugal force load, they would appear to have a number of advantages over hinged blades:

(a) smoothness in operation due to the suppression of the unstable hunting oscillations;

(b) light control forces owing to the blade loads being taken through the aircraft structure and substantially isolated therefore from the controls;

(c) improved dynamic stability by the location of the rotor axes at a considerable distance from the centre of gravity of the aircraft (15% of the rotor radius has been achieved); and

(d) elimination of the sluggishness inherent in the control response of hinged blades.

The Two-bladed Rotor.

Few factors affect the cost of helicopter manufacture more than the present limitation in the number of blades. The simplification of hub and controls that results from a reduction in the number of blades from three to two would make the two-bladed rotor an attractive arrangement were it not for the associated rotor vibration. This vibration is due fundamentally to the variation of the lift, drag and pitching moments of each blade element in proportion to the square of the speed which is itself periodic. These moments are therefore not only cyclic but bicyclic and may be balanced for all practical purposes in a three-bladed rotor but not in a two-bladed one.

Considering a blade element at distance r from the rotor axis, the velocity is

$$w\ r + V \sin A$$

where w is the rotational speed, V the translational speed and A the blade azimuth angle. The lift L_1 of one element is therefore proportional to this quantity squared and may be written

$$L_1 = a + b \sin A - c \cos 2A$$

i.e., the algebraic sum of a constant term, a cyclic term and a bicyclic term.

In a three-bladed rotor, the blades being displaced in azimuth by 120°, the lift of similar blade elements can be expressed as

$$L_2 = a + b \sin (A + 120°) - c \cos 2 (A + 120°)$$

and

$$L_3 = a + b \sin (A + 240°) - c \cos 2 (A + 240°)$$

The sum of L_1, L_2, and L_3 is a constant quantity, viz., 3a, all the periodic terms disappearing.

For a two-bladed rotor, the corresponding expressions are

$$L_1 = a + b \sin A - c \cos 2A$$

and

$$L_2 = a + b \sin (A + 180°) - c \cos 2 (A + 180°)$$

The sum of L_1 and L_2 is

$$2a - 2c \cos 2A$$

which is no longer a constant quantity but contains a term of twice rotor frequency.

Similar expressions are obtained for the variation of lift, drag and pitching moments. Obviously the bicyclic variation of these moments cannot be eliminated by cyclic pitch variation but would require a bicyclic pitch variation. There are, therefore, in a two-bladed rotor, inherent forced vibrations of twice rotor frequency which result from the additive vibration from each blade. The bicyclic vibrations from the several blades of a rotor having more than two blades are in counterphase, and rotors having three blades or more are not subject to this limitation.

It should be mentioned here that, although no means have yet been developed for eliminating these vibrations at the source, they have been rendered comparatively innocuous through the employment of vibration isolation methods. A flight survey has shown that it is possible to minimise the transmission of vibration to the fuselage from a two-bladed rotor sufficiently for practical purposes in small helicopters designed specially to overcome this limitation.

Another method that has been tried is the counter-phasing of two rotors, i.e., counterbalancing the vibration from a two-bladed rotor by an equal and opposing vibration from another similar rotor. As this procedure necessitates the use of four blades, it can scarcely be considered a solution of the two-bladed rotor problem. Except for the counter-rotation of twin rotors to give torque balance, which makes counter-phasing of vibration more difficult, the vibration of twin rotors would be equivalent to that of a single rotor with double the number of blades.

The Single-Rotor Torque Problem

Torque balance is one of the most troublesome limitations of the single main-rotor helicopter and has led to the use of twin contra-rotating rotors, even in small helicopters, in spite of their mechanical complexity. It is a fundamental axiom in dynamics, as expressed by NEWTON in his third law

of motion, that to every action there is an equal and opposite reaction. If the blades are driven by the application of torque at the rotor hub, the fuselage will spin in contra-rotation unless prevented by an external couple such as that arising from the thrust of an auxiliary tail rotor. The torque of the main rotor, being the ratio of the power applied at the hub to the angular speed, can be reduced only by applying some of the available power elsewhere or by increasing the angular speed. The latter alternative is limited by the blade-tip speed which must remain well below the speed of sound to avoid high profile drag losses and by the disc loading which requires a relatively large rotor diameter if a high induced drag loss is to be avoided.

Hence the problem is resolved into finding a method of absorbing some of the available power usefully elsewhere. The powered glider with rotating wings (Fig. 6) conceived by Juan de la Cierva, was one solution. Here the whole of the available power was applied to a forward propeller which ensured the necessary translational speed to keep the rotor revolving

Fig. 6.

at zero torque. A large portion of the rotor blade, acting as a windmill (Fig. 7) absorbed sufficient energy from the air to propel the remainder of the blade (Fig. 8) which, acting in the helicopter state, expended energy on the air. The limitation of the Autogiro as an aircraft of practical utility is that it is fundamentally a glider and can ascend only on tow. Whenever the towing force of the propeller ceases, it must descend. This fact becomes most apparent at take-off and on landing in confined areas, when manœuvres to utilise momentarily the kinetic energy of the rotor are necessary to enable the Autogiro to take-off and land in still air without a

forward run. The inertia take-off is only a palliative, accentuating the necessity of applying power directly to the rotor.

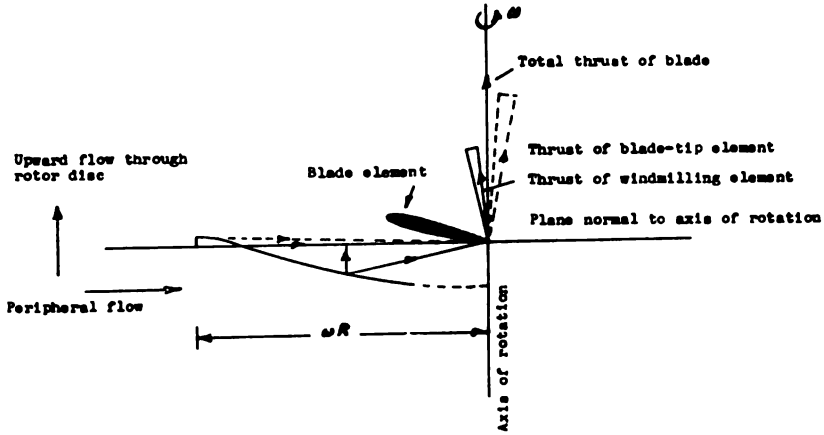

Fig. 7. The mechanism of autorotation.

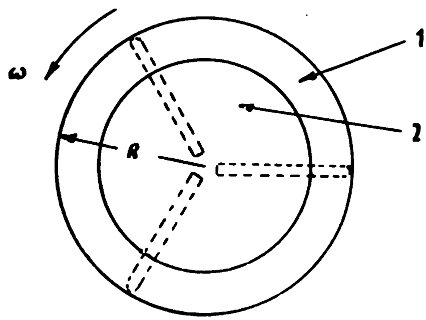

Fig. 8. Torque balance of blade elements in autorotation.

1. *Portion of rotor disc where energy is expended on the air.*
2. *Portion of rotor disc where energy is absorbed from the air.*

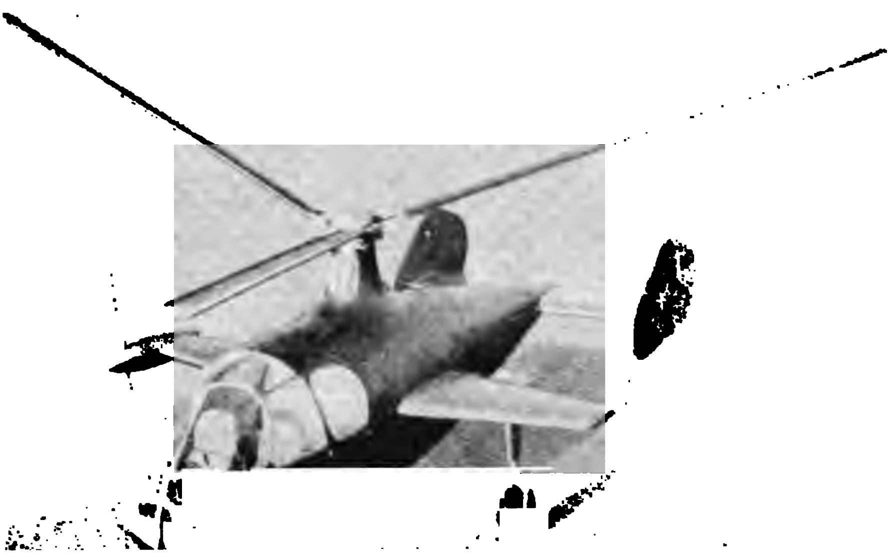

Fig. 9. Gyrodyne.

The gyrodyne (Fig. 9) is an alternative arrangement in which this limitation of the Autogiro may be overcome without sacrificing the advantages of low pitch. The greater part of the available power is utilised for rotor thrust in vertical flight, the remainder being supplied to the propeller which is located outboard for balancing the rotor torque reaction. It is true that in this arrangement power is wasted in vertical flight but the forward thrust of the propeller contributes to propulsion of the aircraft. Provided the disc loading and the available power loading are sufficiently low, the gyrodyne is capable of slow vertical take-off and landing which are the unique advantages of the helicopter.

Similar in principle to the gyrodyne method of balancing torque is the auxiliary tail rotor arrangement developed by SIKORSKY. In one respect this arrangement overcomes the main limitation of the gyrodyne, viz., the large proportion of power applied to the non-lifting propeller, which is useful only in forward flight. To minimise this power loss, the non-lifting propeller must be located as far as possible from the rotor axis and it is then more convenient to support it at the tail than on a long lateral outrigger. There it is known as a rotor rather than a propeller because its thrust is normal to the line of flight and it is subject to similar dissymmetry in forward flight as the main rotor. In fact, the machine is really a twin rotor helicopter. A limitation of this arrangement is the long tail-rotor transmission with the necessary supporting structure and a relatively high disc loading which results in a high induced power loss in vertical flight.

Torque reaction may be avoided entirely by driving each blade at or near the tip instead of at the hub. There are a number of alternative

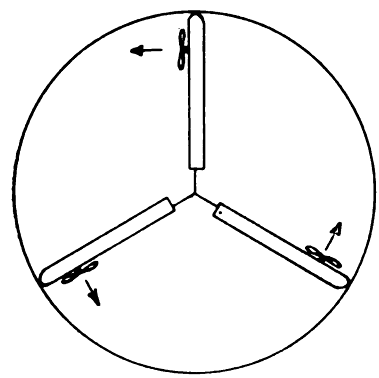

Fig. 10. *Blade-mounted propellers.*

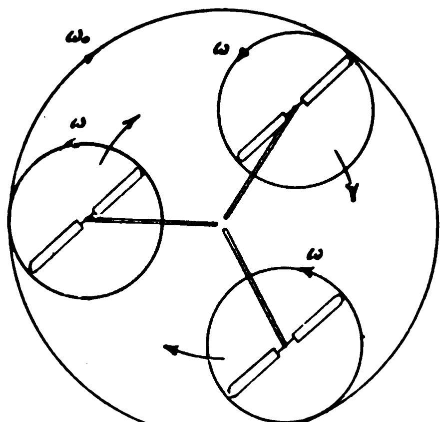

Fig. 11. *Epicyclic rotors.*

arrangements which could conceivably be used to produce thrust at the blade tip. Propellers (Fig. 10) have in the past been mounted on the rotor blades for this purpose and recently blade-tip jets have enabled vertical

flight to be attained by an aircraft that is designed to fly normally as an Autogiro. The high propeller losses, gyroscopic couples and power transmission problems are limitations of blade-mounted propellers and the principal defect of blade-mounted jets at present is concerned with fuel consumption. If and when the fuel combustion problem of small jet units developing relatively low thrust is solved, jet propulsion of helicopter rotors may become a practical proposition. Instead of blade-mounted propellers, one could visualise blade-tip rotors (Fig. 11) which would be powered similarly to the propellers and would rotate epicyclically about the main hub axis, the necessary propulsive thrust being obtained either from the additive torque of the epicyclic rotors or by inclining their tip-path planes in the direction of rotation of the main rotor. A further method is to replace each blade by a system of power-driven paddle blades rotating about a radial axis, the necessary thrust for rotation about the main axis being produced by cyclic pitch adjustment of the paddle blades as in the cyclogyro.

For given values of tip speed, power loading and disc loading, torque increases as the cube of the linear dimensions. Hence the torque problem becomes rapidly worse with increase in size and, unless torqueless rotors can be developed to a practical stage, the use of a single rotor is confined to relatively small machines, large helicopters requiring multiple rotors.

Limiting Power Loading

The minimum power P that would be absorbed by a rotor supporting a gross weight W, if the profile drag were zero, would be that required to give a uniform induced velocity v, where

$$P = Wv.$$

The extreme limit of power loading $\frac{W}{P}$ is equal therefore to the reciprocal of the induced velocity. According to the momentum theory of airscrews, the induced velocity v in ft./sec. at sea level is related to the disc loading w in lbs./sq.ft. by the equation

$$v = 14.5\sqrt{w}$$

Hence the power loading has, as an extreme limit, the value 1/v or, in lbs./h.p.

$$\frac{W}{P} = \frac{38}{\sqrt{w}}$$

A rotor of disc loading 2.3, for example, would not be expected ever to support more than 25 lbs. per horse power in hovering flight away from the " ground cushion ".

In practice, the distribution of lift is far from uniform over the blade length and, as a result, the effective disc loading is greater than the nominal value. In other words, in current helicopters, sustentation is caused by the downward acceleration of air by the rotor blades over an annulus (Fig. 12) of the disc and not over the whole disc. This effect causes the induced

velocity to increase by a factor which appears at present to be about $\frac{2}{\sqrt{3}}$. The induced power loading is therefore, reduced by the reciprocal factor to about $\frac{33}{\sqrt{w}}$.

Fortunately, although the effect of lift distribution is to increase the induced velocity and, therefore, to adversely affect the induced power loading, the induced velocity is decreased at take-off or landing because the

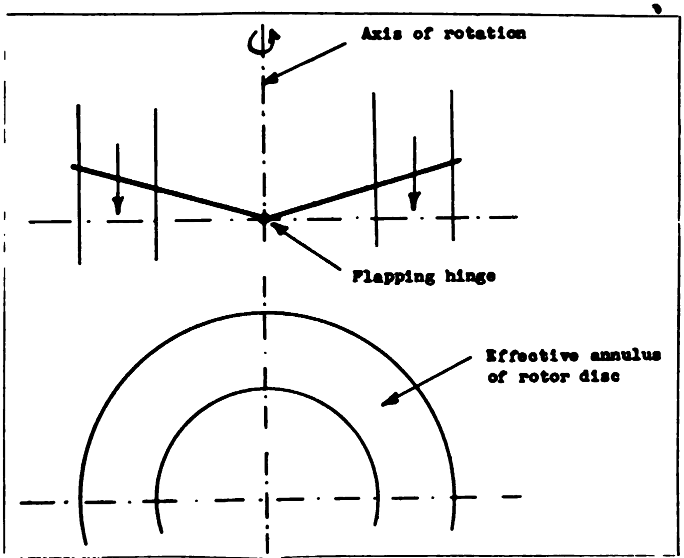

Fig. 12. *Effect of non-uniform flow distribution.*

air is compressed between the rotor and the ground. This cushioning effect of the ground may well enable a helicopter which is overloaded and cannot hover in still air away from the ground, to take-off and land vertically within the "ground cushion"

By definition, the thrust and torque coefficients C_T and C_Q respectively, based on disc area and tip-speed, are related by the equation

$$\frac{W}{E.H.P.} = \frac{C_T}{C_Q} \frac{550}{wR}$$

which can be written

$$\frac{W}{E.H.P.} = \frac{26.8}{\sqrt{w}} \frac{C_T^{\frac{3}{2}}}{C_Q}$$

The ratio of the actual limiting power loading $\frac{W}{E.H.P.}$ to the extreme limit of power loading $\frac{W}{P}$ (for zero profile drag and uniform induced velocity distribution) is

$$\frac{P}{E.H.P.} = \frac{26.8}{38} \frac{C_T^{\frac{3}{2}}}{C_Q}$$

This ratio of limiting induced power to actual power is sometimes referred to as the "figure of merit" or "efficiency" of the rotor and is roughly about two-thirds in hovering flight for the optimum value of $\dfrac{C_T^{\frac{3}{2}}}{C_Q}$

Hence the limiting power loading, taking profile drag into account, is given approximately as

$$\frac{W}{\text{E.H.P.}} = \frac{25}{\sqrt{w}}$$

For example, a rotor of disc loading 2.3 should support between 16 and 17 lbs. per horse-power in hovering flight, at sea level conditions, away from the ground cushion.

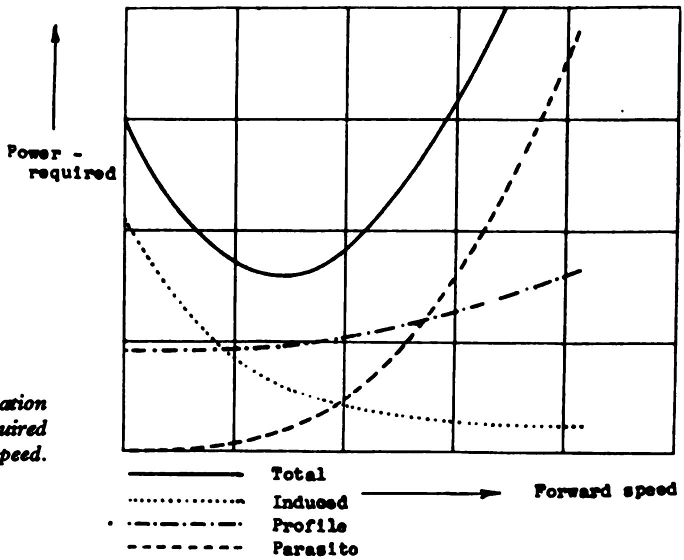

Fig. 13. *Variation of power-required with forward speed.*

When the power loading for vertical flight is exceeded, direct take-off is possible either with the assistance of the ground cushion or by making an inertia take-off as in the jump-start Autogiro. The helicopter may also make a tangential take-off like an aeroplane. The limiting power loading for a take-off with forward speed is nearly double that at zero forward speed (Fig. 13) because, at the forward speed (usually about 50 m.p.h.) where the power required is a minimum, the induced power is only a fraction of its value for hovering flight whereas the profile drag and the parasite drag change the power required relatively little at low airspeeds.

Pitch Limitations

Variation in rotor pitch is required

(a) to vary the rotor power independently of angular speed;
(b) to compensate for the change in angle of attack of the blades due to the variation in axial flow through the rotor disc with forward speed; and
(c) to compensate for the change in density of the air with altitude.

The necessity for control simplification has resulted in the development of devices for governing rotor pitch or engine speed, thereby eliminating a separate pitch control or a separate throttle control respectively. In the one case there is an automatic pitch reduction in the event of power failure and, if this occurs near the ground, the sudden reduction in pitch and consequent loss of lift before steady autorotation is established may cause the helicopter to land at an excessive sinking speed. In the other case, the pilot retains control of pitch and may utilise the kinetic energy of the rotor for momentary hovering prior to a power-off landing, but there is a risk of over-control in flight. When this occurs, an increase in pitch causes the aircraft to sink rather than climb, the rotor blades slowing down and eventually stalling.

The immediate reduction in pitch on power failure is an essential requirement for those helicopters which operate at a pitch beyond that at which the blades will autorotate. A simple calculation shows that the kinetic energy of the rotor is sufficient only for a very few seconds of power-off flight when the limiting autorotative pitch is exceeded. For a rotor of total blade weight equal to six per cent. of the gross weight (W lbs.) of the aircraft, the kinetic energy in lbs. ft. is roughly $\frac{W}{3000}$ times the square of the tip speed in ft./sec. If the E.H.P. at the operating speed is six per cent. of the gross weight, energy is absorbed by the blades at the rate of 33 W lbs.ft./sec. Therefore, the whole of the kinetic energy of the rotor is expended by the blades every *t* secs. where

$$t = \frac{1}{10}\left(\frac{wR}{100}\right)^2$$

i.e., two and a half seconds if the tip speed is 500 ft./sec. In other words, the inertia of the rotor will not prevent the blades from rapidly decelerating at high pitch. Hence the necessity for automatic pitch reduction in the event of power failure.

The risk in operating helicopters beyond the limiting autorotative pitch can be lessened by the provision of twin power plants, but it is not essential for helicopters to take this risk at all. The power can be absorbed equally well at low pitch by a rotor of low blade loading or high tip speed, except at very high altitudes.

A further high-pitch limitation is one associated with the forward inclination of the rotor for propulsion (Fig. 14). The rotor disc then makes a negative angle of incidence with respect to the flight path, thereby causing the axial flow through the rotor to increase with forward speed and change the blade angle of attack unequally from root to tip. Least affected by a change in axial flow is the tip portion of the blade. Consequently, when the main collective pitch of the blades is increased to compensate for the increased axial flow, the blade angle at the tip becomes excessive and may approach the stall cyclically at high transational speeds where the angle of attack on the retreating blade is already high due to blade flapping or cyclic feathering. This periodic variation in lift distribution at maximum speed not only impairs the propulsive efficiency of

the forwardly inclined rotor but limits the operation of the helicopter to the inherent roughness at the higher airspeeds.

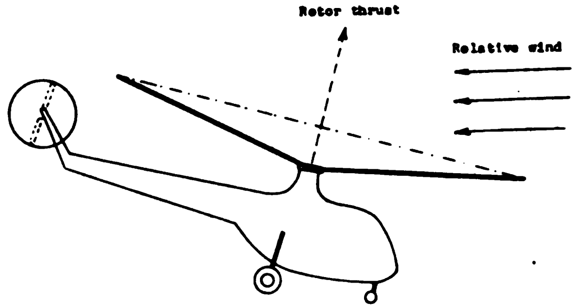

Fig. 14.
Propulsive rotor.

Limiting Translational Speed

Although the compressibility of the air no longer appears to be an insuperable barrier to the speed of fixed wing aircraft, it is still a serious limitation in regard to the horizontal speed attainable by helicopters. Even if boundary layer control and jet propulsion can be applied successfully to rotor blades, the fluctuation in relative air speed and therefore in lift coefficient at the blade tip is so great at high forward speeds that bending and torsional deflections of the blade and their effect on vibration and airworthiness of the aircraft would appear to place a definite limit on

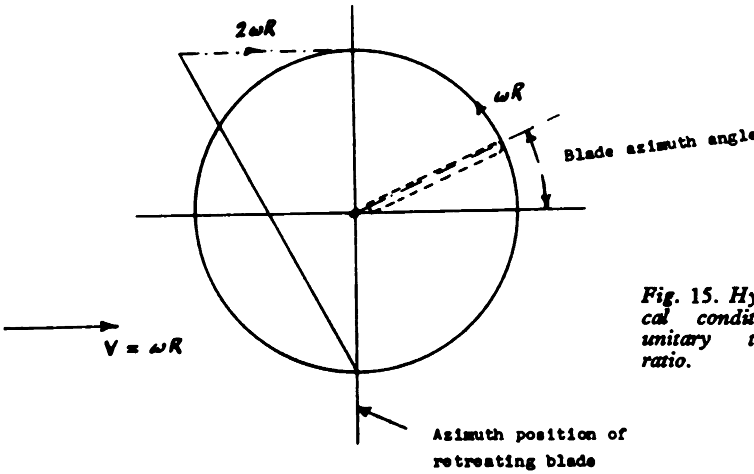

Fig. 15. *Hypothetical condition of unitary tip-speed ratio.*

forward speed. This limit is governed by the maximum relative air speed permissible at the tip of the advancing blade and it is not anticipated that this will exceed about 3/4 of the speed of sound.

With regard to tip-speed ratio, i.e., the ratio of forward speed to the steady peripheral speed at the blade tip, this ratio was as high as 2/3 in early Autogiros and it has been suggested that it could ultimately be increased to unity (Fig. 15) in which case the tip of the retreating blade would have zero air speed and the remainder of the retreating blade would have negative air speed. The lift of each blade would then have to fluctuate from zero in each of the two lateral azimuths to its maximum

value in the fore and aft azimuths. It is thought that vibration will limit the tip-speed ratio of helicopters to about 2/3 for a long time to come. This corresponds to a limiting forward speed of 0.3 of the speed of sound if the relative air speed at the tip of the advancing blade is limited to 3/4 of the speed of sound.

It is unlikely, therefore, that helicopters will be developed to fly eventually at much over ¼ of the speed of sound, which, at sea level, corresponds to less than 200 m.p.h.

Limitations in Size

Strange as it may appear at the present time when large helicopters are being contemplated as a matter of course, it was only a few years ago that the proposal to develop helicopters for shipboard use met with considerable opposition because of the contention that the limiting size of helicopter would be one carrying a maximum useful load of slightly over half a ton. The argument behind this assertion was that the rotor weight would increase as the cube of the rotor diameter and the gross weight only as the square. Consequently, the rotor weight would become such a large proportion of the gross weight that the useful load would eventually tend to zero.

Rotary wing experience had shown that it was possible to keep the ratio of rotor weight to gross weight practically constant, independent of size. In a rotor blade consisting essentially of a main spar to carry the centrifugal tension and an outer shell to give aerodynamic shape and stiffness, all the dimensions did not require to be increased in the same proportion as the size increased. The thickness of the skin could remain substantially constant and it was easy to show that for constant tensile stress in the spar and for constant blade-tip speed, the area of the spar needed only be proportional to the rotor diameter. These broad arguments suggested that the blade weight would be a constant proportion of the gross weight.

While the English-speaking nations were debating whether the cube law or square law applied to rotor size, with the destiny of the helicopter at stake, Germany (or as Dr. Sissingh is present, shall I say: half of Germany) had already decided that the law was a linear one and that the ratio of blade weight to rotor weight was therefore inversely proportional to the diameter, an increase in size resulting in an increased proportion of useful load. Here then are three different laws that give widely different results. Which of them is correct?

The answer is that they are all correct, but they apply to separate ranges of rotor size. The three factors that govern the ranges are:

(a) Angular speed (b) Blade-tip speed (c) Coning angle

The ratio of rotor weight to gross weight is inversely proportional to the product of these three quantities. The linear law applies when the angular speed and coning angle are kept constant and the blade-tip speed is increased with rotor size. When the limit of blade-tip speed has been reached (at present just over half the speed of sound) the square law begins to apply. In this case, the angular speed varies inversely, and the coning angle directly, with rotor diameter, the blade-tip speed remaining constant.

When the coning angle and therefore the downwash gradient become excessive (apparently about one-sixth of a radian—or $9\frac{1}{2}°$) rotor vibration limits the range of size to which the square law applies. Beyond this limit, with coning angle and blade-tip speed constant, the rotor weight increases as the cube of the rotor diameter for a given value of disc loading. An increase in disc loading with size does not affect this question very much because, as we have seen, the limiting power loading decreases with increased disc loading.

For a total blade weight equal to six per cent. of the gross weight and a coning angle in hovering flight, of one-tenth of a radian (about $5\frac{3}{4}°$) the limiting rotor diameter, beyond which the blade-tip speed cannot be increased, is about 50 feet. Beyond this diameter, the coning angle must increase and reaches the present limit of one-sixth of a radian at a diameter of 84 feet. Until rotor vibration at larger coning angles can be kept within practical limits, rotor diameters in excess of 84 feet can be used only at the expense of percentage useful load, unless a corresponding saving can be effected in the percentage weight of other items.

Certain items of the rotating system other than the blades themselves will also be affected by the cube law. A useful load equal to one-quarter of the gross weight has already been achieved and, if the cube law applies to one-eighth of the present gross weight, the variation in useful load for rotors above 84 feet diameter is proportional to

$$\frac{3}{8}\left(\frac{d}{84}\right)^2 - \frac{1}{8}\left(\frac{d}{84}\right)^3$$

It can be shown that this quantity is a maximum when d = 2 x 84 and becomes zero when d = 3 x 84. Hence the cube law for blade weight variation gives a limiting useful load per rotor of about 3 tons at a rotor diameter of 168 feet. Beyond this size the useful load would decrease and tend to zero at a diameter of about 252 feet.

I think you will agree that the cube law does not forecast too limited a future for the helicopter.

Dynamic Stability

At one time it was thought that the dynamic instability of single main-rotor helicopters about their rolling and pitching axes in the hovering condition would be a major limitation and that it would be necessary to devise means for overcoming this defect before practical helicopter flight could be achieved. Experience with existing helicopters has shown that dynamic instability at zero forward speed may be relatively unimportant.

The rolling or pitching motion of the helicopter, following a small disturbance, possibly the result of a gust, is statically stable if the initial tendency of the helicopter is to return to its equilibrium condition. This is ensured by the high position of the rotor above the centre of gravity of the aircraft.

Dynamic stability is concerned with the subsequent motion (Fig. 16), which may be either non-periodic (in which case it is stable) or oscillating, in which case it is stable if successive oscillations are of decreasing amplitude but unstable if they are divergent. Both stable and unstable oscillations are characterised by:

(a) the period of time required for one complete oscillation ; and
(b) the damping or amplification factor which determines the rate at which the amplitude of successive oscillations decreases or increases respectively.

It is found that in certain present-day helicopters where the period of

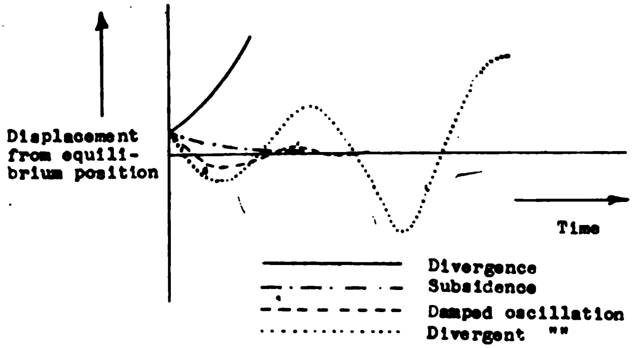

Fig. 16. *Motion of aircraft following a small disturbance.*

oscillation is about 12 secs. and the time required to double the amplitude is 18 secs., the unstable motion is not at all critical or difficult to control.

The equations of motion of the aircraft (Fig. 17) when expressed in terms of angular displacement and linear velocity as independent variables, result in an equation of the form:

$$An^3 + Bn^2 + Cn + D = 0,$$

where n is the frequency of the oscillation and C = 0 if the variation in inclination of the tip-path plane with respect of the axis of rotation is small compared with the amplitude of oscillation of the helicopter.

The condition for stability is that the roots of the frequency equation should be real and negative, or imaginary with their real parts negative, and ROUTH has shown in his textbook "Advanced Rigid Dynamics" of 1892 that this condition is satisfied provided the coefficients A, B, C and D are positive and, in addition,

$$BC > AD$$

So long as C =0, therefore, the aircraft must be unstable.

In other words, the tip-path plane must be prevented from oscillating with the same amplitude as the body of the aircraft. It can be shown that if the oscillation of the tip-path plane is reduced in amplitude by *a* times the amplitude of oscillation of the body, C is no longer zero and the condition for dynamic stability can be satisfied. If *l* is the distance of the rotor hub above the centre of gravity and *k* is the radius of gyration of the aircraft about the rolling or pitching axis, *a* must satisfy the inequality

$$a > \frac{1}{1 + \frac{l^2}{k^2}}$$

For example, if $l/k = 3/4$, *a* must be about 2/3, i.e., more than 2/3 of the oscillation of the tip-path plane must be suppressed if complete dynamic stability is required.

This result applies to the motion about the pitching and rolling axes of single main-rotor helicopters but is applicable also to the pitching oscil-

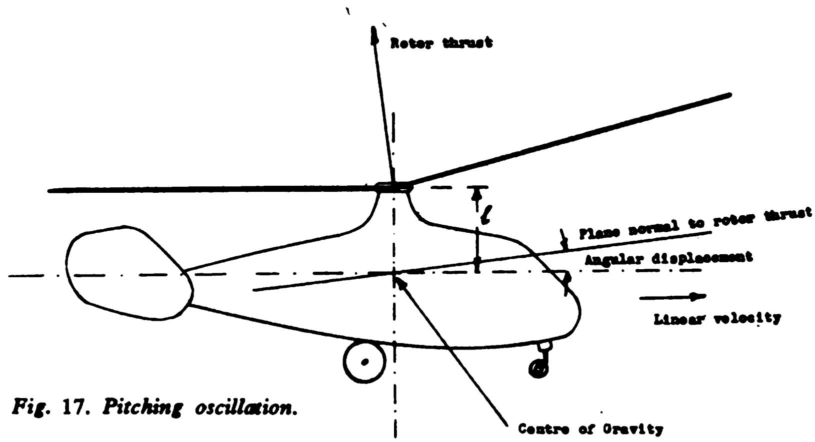

Fig. 17. *Pitching oscillation.*

lation of laterally-disposed twin rotors and to the rolling oscillation of twin tandem rotors. In multi-rotor helicopters any angular oscillation of the aircraft that causes the axial flow through one or more rotors to vary is heavily damped and dynamic stability can be provided without difficulty.

The Technical Outlook

It may be a very long time before we have perfectly stable, jet-driven, hingeless, two-bladed, large-sized, single-rotor helicopters that will operate smoothly and safely in every condition of flight ranging from zero translational speed to a quarter of the speed of sound. It may be many years before the helicopter is as fully developed as the aeroplane or as easy to handle as a car, but at least it has emerged from the laboratory stage. In spite of its present limitations, it is already established as a vehicle of practical utility—not a competitor of the aeroplane or other forms of transport but with unique uses of its own. The aeroplane will always be more suitable for long journeys by air, just as rail transportation is preferred to long journeys by road. The helicopter, like the car, will have its own restricted uses—I hope much more so, because although the helicopter can be brought safely to a standstill in flight, an air traffic jam over the cities is unpleasant even to contemplate.

Of the multifarious versions of the helicopter now under development throughout the world, the single main-rotor helicopter with a rotary tail unit—a configuration that must ever be attributed to IGOR SIKORSKY—appears to be the best compromise for low-powered machines of relatively low cruising speed. So long as vibration continues to be an important limitation in translational flight, an orthodox propeller may be preferred to the forwardly-inclined rotor for the propulsion of helicopters of high cruising speed and low power loading.

The rapid increase in rotor torque with size restricts the use of a single main-rotor to relatively small helicopters, unless jet assistance for vertical flight becomes practicable, in which case large single-rotor helicopters could operate in forward flight at reduced torque as a gyrodyne or at zero torque as a gyroplane. For larger machines, twin rotors, mounted in tandem, and possibly intermeshed, would seem to be the most straightforward arrangement at the present stage of development.

The Second Annual General Meeting of The Helicopter Association of Great Britain

REPORT

The Second Annual General Meeting of the Association was held in the Lecture Hall, Manson House, 26, Portland Place, W.1., on Saturday, 22nd March, 1947, at 2.30 p.m.

After reading the Notice convening the Meeting the Hon. Secretary read apologies for absence and the following ship's telegram from G/Capt. LIPTROT, Dr. BENNETT and W/Cdr. BRIE, who were on their way to the U.S.A., was read:

> "Many Happy Return First Anniversary. Best Wishes for successful Meeting and Dinner—Doc., Reg. and Loopy."

The Minutes of the First Annual General Meeting were read and adopted.

The CHAIRMAN then presented the Annual Report, and since it had been circulated to Members prior to the Meeting he asked those present to take it as read. No comments were made nor objections raised, and the Report was unanimously adopted.

The HON. TREASURER then presented the Annual Accounts, and called the attention of Members to the fact that the Association had ended its first financial year with a credit balance of some £50.

Mr. M. S. HOUDRET moved the adoption of the Annual Accounts, and Mr. G. A. FORD seconding, these were adopted.

The CHAIRMAN presented the audited statement of the result of the ballot for election of the Council for the year 1947, and the following Members were elected:

> H. A. MARSH, A.F.C., A.F.R.Ae.S. (*Chairman*); J. A. J. BENNETT, D.Sc., F.R.Ae.S.; C. G. PULLIN, F.R.Ae.S., M.I.Mech.E.; F. F. CROCOMBE, B.Sc., F.R.Ae.S.; R. A. C. BRIE, A.F.R.Ae.S., A.F.I.Ae.S.; H. M. YEATMAN, M.A.(Cantab.), A.F.R.Ae.S.; A. CARPMAEL, A.I.A.E.; N. J. G. HILL, A.M.I.A.E., A.R.Ae.S.; S/Ldr. F. J. CABLE, R.A.F.; G. C. TURNER, A.F.C.; F/Lt. J. E. HARPER, A.F.C., R.A.F.; R. HAFNER; R. N. LIPTROT, G.B.E., B.A.(Cantab.); O. L. L. FITZWILLIAMS, B.A.(Eng.)Cantab.; B. H. ARKELL, A.R.Ae.S. *Hon. Sec.*: M. J. B. STOKER; *Hon. Treas.*: G. C. TURNER.

Mr. C. G. PULLIN moved that Messrs. W. B. KEEN & Co. be appointed Auditors for the ensuing year. This was seconded by Mr. K. WATSON and unanimously agreed.

After the CHAIRMAN'S speech Mr. M. STOKER proposed on behalf of the Members a vote of thanks to the Chairman and Council for the work which they had done during the past year. This proposal was seconded by Dr. THURSTON and carried unanimously.

Some discussion ensued on the question of an Association emblem, and it was finally agreed that a small sub-committee should be formed to examine suggestions and make their recommendations to the Council. The

following Members expressed their willingness to serve on the sub-committee: Major NELSON, Mr. DIXON, Mr. J. ROGERS together with two Members of the Council to be appointed.

Further discussion followed on the question of a programme of activities for the year 1947/48 and the Meeting closed at 4.15 p.m.

CHAIRMAN'S SPEECH

Gentlemen,

As you will have seen from the Annual Report and Balance Sheet, membership of the Association has increased in a very satisfactory way and is, I think, a very good index of the interest being shown in the development of the helicopter.

Applications for membership continue to come to hand but I urge you to exert every effort to persuade those who, in your opinion, are qualified in accordance with our Rules to make application for membership. Every new member means increased income and although the Balance Sheet shows that the Association is solvent, we have by no means reached the goal for which we aim, that is to say, sufficient income to provide funds for the establishment of a full-time Secretary, together with office accommodation, staff, etc.

We have received, as you will observe from the Balance Sheet, several substantial donations from Members and others, and I wish to express the keen appreciation of the Council to all donors of such gifts.

In addition, the Association has been given by a member who wishes to remain anonymous, the sum of £100 to be devoted to prizes for essays covering various aspects of helicopter activities and it has been agreed that this sum should be split up into four annual prizes of £25 each. You will be aware of the conditions and so on of this current year's competition and it is hoped that we shall be able to establish this as an annual event, and possibly introduce other prize competitions of similar interest.

With the completion of the first year of its existence, a few words on the working of the Association may not be out of place. Your Executive Council have met on 17 occasions in order to conduct the general business of the Association and five very successful lectures have been organised in addition to an informal discussion and film display in the House of Commons, which was given at the request of certain Members of Parliament.

An invitation was received during the year from the Ministry of Civil Aviation to criticise and advise upon the helicopters Civil Specifications, and also the proposed regulations for the operation of helicopters and the issue of Licenses to Pilots.

In other directions, several of our members have a place on the various committees sets up by the Ministry and Aeronautical bodies to consider problems associated with general development.

Very satisfactory relations exist between the Association and all other aeronautical bodies and in our work we have received every assistance from

the Royal Aeronautical Society, Royal Aero Club, Guild of Air Pilots and the Society of Licensed Aircraft Engineers, and we continue to work in very close harmony with all these bodies. We have also received every encouragement from the Helicopter Society of America and some of their members have already joined our Association. A very close liaison with this Society is maintained through one of our Council members, who represents the Society over here.

You no doubt remember the formation of another body with somewhat similar aims to our own, and you may also remember that we discussed the possibility of a merger with that body at our First General Meeting in March of last year. A merger sub-committee was formed by us and several meetings took place with an equivalent committee from the other body, but unfortunately after much patient work it was found impossible to continue with the negotiations, which have therefore been terminated.

The Helicopter Association Bulletin has been published on two occasions and a third issue would by now have been in print had not the present fuel and power emergency arisen. It is hoped, however, with the resumption of more normal conditions to despatch the third issue to members in a very short time. In its present form the Bulletin is a very modest production, but as our membership grows and funds accrue, it is hoped to improve and add matter to it so as to widen its interest to members generally.

In order to relieve the general funds of the cost of publishing and preparing this Bulletin, an invitation was recently extended to certain concerns engaged in and around the aircraft industry asking that they take space in the form of a token advertisement in our Bulletin, in return for a small fee. The response to this invitation is most encouraging and it is intended that we shall continue with this form of publicity.

While on the matter of finance, I am able to say that although our membership continues to grow—totalling as it does at the present day 161—the working expenses of the Association have been kept to a very low level only by the energy and enthusiasm of the Members of the Executive Council, who have at considerable personal inconvenience given up time and gone to considerable expense in the execution of certain duties which, as your Chairman, I have had the honour to allocate to them from time to time. These conditions can only continue for a very short time, because with the growth of the helicopter movement, individuals who have given up so much of their time will be unable to devote as much time to the Association's affairs as heretofore. Therefore, the appointment of a permanent Secretary with office accommodation, etc., becomes more and more urgent and you are again urged to do all you possibly can to increase the membership so that our aims may be accomplished.

Also on the subject of membership, I am sure you will all be glad to hear that your Council has unanimously elected the first Honorary Member of the Association in person of JUAN DE LA CIERVA, the eldest son of the late Senor de la Cierva, as some small token of the esteem in which the memory of his father is held.

The Council have for some time given thought to an Association emblem and members have been requested to submit designs. We do not wish to rush this matter but I think we are all agreed that an emblem is desirable and we shall therefore welcome any further designs or your views upon this question.

Before closing, I desire to place on record the Association's appreciation of the work carried out by our Auditors, Messrs. W. B. Keen & Co. The partnership has taken a great interest in the Association since its formation and, further, their interest has been reflected in the kindly manner in which they have permitted the Association to make use of the premises at Finsbury Circus House, and the very low fees charged for professional and other services.

I desire also to say how we appreciate the advice and guidance which has been given so unstintingly by Mr. E. C. Rogers on the many occasions when it has been necessary to approach him. It is hardly too much to say that our finances would look anything but healthy except for the amount of gratuitous work put in by Mr. Rogers and his Staff.

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THE FIRST DINNER, 1947

Following the Second Annual General Meeting the Association held its first Dinner on the evening of March 22nd, at The Old Red House in Bishopsgate in the City of London. The hope had previously been expressed that this would become an annual function, and such was the enthusiasm which greeted the proceedings, that there seems little doubt that this hope will be fulfilled. In all, some 75 members and guests attended.

Among the guests present were Captain J. Laurence Pritchard of the Royal Aeronautical Society, and Colonel R. L. Preston of the Royal Aero Club. The presence of directors of four of the major aircraft companies now projecting helicopters in this country was indeed very welcome, as was, of course, the presence of the technical press.

In replying to the toast of " The Guests ", Colonel Preston stressed the importance of the Association being represented at the meetings of P.I.C.A.O. and very kindly offered the Association use of the facilities available at Londonderry House.

Captain Pritchard, following with the toast " The Helicopter Association ", made some witty and very entertaining comments on the dangers of flying fixed wing aircraft, and welcomed the enthusiasm of the Association in embarking on the problems of rotating wings. He extended an invitation to the Chairman of the Association to use facilities at 4, Hamilton Place.

The Chairman, Mr. H. A. Marsh, thanked the guests on behalf of the Association, expressing his keen appreciation of their good wishes and further, for their very practical offers of assistance.

THE JOURNAL OF

HE HELICOPTER ASSOCIATION

OF GREAT BRITAIN

VOL. 1. No. 2.

1947

The Journal of

THE HELICOPTER ASSOCIATION OF GREAT BRITAIN

Publications Committee: E. G. Smettem (Chairman), B. H. Arkell, M. J. B. Stoker (Hon. Sec.).

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Editorial.

This issue, the second number of "The Journal," brings with it the close of a year which has been somewhat eventful both in helicopter development in England and for the Helicopter Association of Great Britain, and it may not be inappropriate to review briefly the events of 1947 in both respects.

On the development side, there have been several convincing demonstrations of the practical application of helicopters to everyday life. Outstanding among these being such demonstrations as the flight of the Parliamentary Secretary of the Ministry of Civil Aviation from his home in the country direct to the heart of London, the landing of a helicopter in the Horse Guards Parade, the recent demonstration to the Elder Brethren of Trinity House when the Vice-Chairman of the Council of the Association was picked up by winch and cable from the gallery of the Dungeness Lighthouse and lowered into a life-boat on a choppy sea; thus demonstrating in this country the ability of a helicopter to rescue marooned crews of lighthouses or lightships. A more recent demonstration was the landing of Captain Lamplugh on a bombed site in front of his offices in the heart of the City.

Two British helicopters were on show at the S.B.A.C. Exhibition in September and a third has successfully undergone initial flying trials. British European Airways have formed a Development Flight to explore the practical application of helicopters as an ancillary to scheduled air services. Public interest in helicopter flight has been considerably stimulated.

As far as the Association is concerned, membership has increased during 1947 by 65 members. The Association has become accepted by official and technical bodies as a source of information and an authority on all matters pertaining to rotary wing flight. A number of authoritative and interesting papers and lectures have been read to members and their guests by leading scientific, technical and practical authorities on the science of rotating wing flight. By no means least among these being a most interesting talk by Mr. Igor Sikorsky during his visit to England in September.

It is the Association's aim to embrace all branches of interest in the development of rotating wing flight; the scientific, the technical, operational, practical, and particularly the student interest.

The Association's activities on behalf of members are, of course, limited by its income, which is, for the greater part, derived from members' subscriptions. Increased income from membership will broaden the Association's activities and enable it to do still more to promote development and interest in rotating wing flight. The Council, therefore, appeals to each member to strive to enrol at least one new member during 1948.

DINNER TO MR. I. SIKORSKY.

On the evening of September 8th, 1947, a small informal dinner was held at which Mr. Igor Sikorsky was the guest of honour.

Other overseas guests were Mr. Grover Leoning, Mr. J. S. McDonnell, Mr. F. N. Piasecki, Mr. W. W. Kellett and Mr. Robert H. Stanley.

The dinner was given by the members of the Executive Council of the Association who were joined as hosts by Mr. F. L. Massey-Hilton, Mr. J. Fearn, Mr. E. Mensforth and Capt. Uwins. Mr. Arthur Carpmael was responsible for the arrangements and obtained the permission of the Master for the dinner to be held in the Hall of the Worshipful Company of Armourers and Braziers. The informality of the function made considerable appeal to the guests, as did the beauty and antiquity of the Hall and the craftsmanship of the armoury exhibits.

After toasts had been proposed to H. M. the King and The President of the U.S.A., Mr. R. A. C. Brie, in a short and apt speech welcoming the guests, drew a contrast between the antiquity of the Company in whose Hall the function was being held and the craft which it represented, and the modernity of the science and craft represented on this occasion.

Mr. Grover Leoning responded on behalf of the guests. At the Chairman's request, Mr. Carpmael, a Past Master of the Worshipful Company of Armourers and Braziers, gave some interesting details of the history of the Company and of the Hall, which was very much appreciated.

SOCIETY OF LICENSED AIRCRAFT ENGINEERS AND HELICOPTER ASSOCIATION OF GREAT BRITAIN (JOINT PANEL).

A Joint Panel representing the Society of Licensed Aircraft Engineers and the Helicopter Association of Great Britain has been formed to consider and discuss with the Air Registration Board requirements for Helicopter Maintenance Engineers' Licences and the endorsement of licences to cover helicopter maintenance. The Panel is composed as follows :—

SOCIETY OF LICENSED AIRCRAFT ENGINEERS :

- MR. W. J. ANDREWS, Chairman of the Council.
- MR. D. W. RICHARDSON, Vice-Chairman of the Council, and Chief Instructor Messrs. de Havilland's Technical School.
- MR. M. T. HOLDHAM, Member of the Council, and Instructor Messrs. de Havilland.

HELICOPTER ASSOCIATION OF GREAT BRITAIN :

- MR. G. B. L. ELLIS, Chief Development Engineer, Helicopter Division, Fairey Aviation.
- MR. A. MCCLEMENTS, Experimental Engineer B.E.A. Helicopter Unit.
- MR. J. LEASON, of B.E.A. Helicopter Development Flight, Helicopter Engineer.

NEW MEMBERS.

The following have been elected to membership since the last published list.

MEMBERS.—J. R. Anderson, L. S. Armandias, N. A. Adler, R. von Bahr, A. C. Barlow, E. L. Bird, R. B. Brigham, R. H. Bryant, N. J. Capper, C. Cullimore, A. Davenport, V. Dibovsky, A. D. Duncan, S. W. Farley, J. Fearn, G. N. C. Fuller, W. Garrow-Fisher, G. W. T. Gray, W. W. Hackett, R. Hafner, J. C. Hendra, F. L. Hodgess, L. L. Irvin, R. F. Lane, I. M. D. Little, Y-S. Lung, N. L. Lupton, E. Mensforth, A. J. Mollart, R. L. Napier, J. S. Neale, R. Oakes, A. E. Page, A. J. Pegg, W. H. Perry, G. J. Sissingh, G. H. Tidbury, K. W. Turner, S. B. Weller, R. H. Whitby, J. K. Williams.

ASSOCIATE MEMBERS.—A. H. R. Baker, E. K. Bailey, A. J. Bristow, O. V. Brooks, R. E. Burns, K. Charles-Batson, J. F. Fewell, L. P. Gibson, L. H. Hayward, J. D. Hayhow, M. P. Hanvey, T. Harrison, N. E. Ingpen, A. S. Johnston, Mrs. E. Nelson, E. J. Ockelford, H. J. Parham, H. J. Penrose, G. T. Perkins, D. M. Ridgway, J. S. Rivaz, P. F. Reed, J. D. Rogers, D. A. Smith, C. Turner, R. W. Usher, A. R. Yates.

GRADUATE MEMBERS.—I. A. Anderson, D. D. Bamber, H. D. Barr, Miss M. Cade, C. P. Drury, A. E. Gale, N. A. Harper, G. G. Hunt, G. Meyrick, S. Mills, W. N. Patrickson, Miss E. Potts, C. Ridley, Miss M. Wilkins, L. A. Wingfield.

FIFTH LECTURE 1947

Sikorsky Helicopter Development

By IGOR SIKORSKY

A lecture presented to the Helicopter Association of Great Britain on Saturday, 8th September, 1947, at Manson House, 26 Portland Place, London, W.1.

H. A. MARSH, A.F.C., A.F.R.Ae.S., IN THE CHAIR

INTRODUCTION BY THE CHAIRMAN.

Ladies and Gentlemen,

It is my privilege this evening to introduce to you MR. IVOR SIKORSKY, the eminent engineer responsible for the design and development of the helicopters bearing his name. He is going to talk to us about the recent developments of these aircraft.

I think it is correct to say that MR. SIKORSKY is the earliest pioneer of helicopters alive today, having been engaged upon experimental work with this type of aircraft as far back as 1910, and he also has the distinction of being the first to produce the helicopter as a realistic and practical aircraft.

We have to thank two of our Council Members—Dr. Bennett and Wing-Cdr. Brie—for suggesting to MR. SIKORSKY that he should give us this talk and we all very much appreciate MR. SIKORSKY's gesture in consenting to do so.

On behalf of the Association may I extend a very cordial welcome to all our guests.

MR. IGOR SIKORSKY.

MR. CHAIRMAN, ladies and gentlemen, I consider it an honour and privilege to address you tonight on the subject of helicopters, which has been a subject of very great interest to me in the last fifty years or so.

About the year 1900 I tried to make models of helicopters ; later on, when 19 years or so of age, I became so firmly interested that I decided to go into this aviation game. The first aircraft that I built was a helicopter.

The reason for deciding on the helicopter was partly serious and partly instinctive, or I may say, romantic. The idea of flying existed in the world for nearly 600 years—very much earlier than any idea of the locomotive or automobile. Always people associated the dream about flying with the solution of two problems—one was that of travel through the air. This, as we know, has been partly solved by the aeroplane. But there was a second problem to solve, the problem of free take-off and free landing on any spot of the earth. In this respect, the aeroplane proved to be the most helpless vehicle ever designed by man, because an aeroplane operates with safety only in a large space. Obviously, the problem of travel was not really solved by the aeroplane, but could be solved by another vehicle that could rise quickly from a confined space, stay over one spot, go quickly down and land on any spot—a roof-top or anywhere else where there is room. For years that was a dream, but behind such dreams there has been a very great deal of technical construction. Only a few years ago mention of the subject was thought a stretch of the imagination. Now, fortunately, things are different.

It is known that the helicopter has already accomplished things—there is a great deal of work done by the helicopter in spite of its very short career. During the last year of the war helicopters were quite extensively used in the Pacific, India and Burma. They were used for various rescue missions and a number of soldiers owe their lives to the possibility of being rescued by helicopter after descents and crashes behind the enemy lines. A number of other valuable services have been rendered ; for instance, helicopters have been used on board transport ships which were supplying spare parts. In the most urgent cases spare parts could be taken from shipboard whilst the vessel was still steaming in the sea, and flown to those parts where they were most needed.

In a number of cases B.24's and other large airplanes were kept in the air by the possibility to obtain quickly the necessary spare parts supplied by helicopter.

There has been a number of other uses and by the end of the war the worth of the helicopter had been proved and now valuable information can be given in spite of a very short time after the end of the war. Let us take a few cases at random. Helicopters have been used for crop-dusting and undoubtedly their use will extend further, the value of this work justifying substantial expansion. Another important use is fighting forest fires. Nothing can be so valuable in controlling the fire as getting quickly to the beginning of the fire, when in ten minutes two or three men could extinguish it.

There are other important things such as cargo carrying. Strange as it may look at first, the employment of the aeroplane increases the necessity for some adequate service that will deliver mail to the airport, take it from the airport and distribute it quickly. The average air-mail letter from Chicago to Los Angeles has taken much more time in covering a dozen miles at both ends than it has taken in the air to cover the distance (about 2,000 miles) between Chicago and Los Angeles. Tests have recently been conducted and they have proved an outstanding success. As soon as the mail plane arrived at the airport three helicopters were filled with mail. Three craft were necessary because in the Los Angeles area it was necessary to visit about 45 places. In these places the helicopter could land sometimes

on the roof of the Post Office, sometimes in the back yard and sometimes very close to the delivery point. The letters were then sent out right away to their destination. The saving in time was considerable, amounting occasionally to from 10-24 hours.

Next, of course, we come to actual passenger carrying. This is perhaps the main and most important job to perform for the helicopter at the present time. The value of the helicopter in this respect is obvious. In spite of its low speed it will be by far the fastest vehicle for distances of 50-100 miles, taking into account the time necessary to go the the airport. I know, for instance, that in our case the helicopter is now a very regular instrument for

The Sikorsky S.51.

ferrying men of our factory who go by air. It takes us about half an hour to drive to the airport, whereas it takes two or three minutes to fly a helicopter to the airport. The importance of passenger transport by helicopter literally cannot be estimated. I have not the slightest doubt that in future this will be as important in our every-day life as airplanes are today.

Undoubtedly one of the most romantic and interesting services rendered by the helicopter was the large number of rescues. It is of great satisfaction to all of us working in the helicopter field that it should be a means of saving life—life that in a great many cases could not have been saved by any other vehicle. I cannot repeat all the details of these rescue missions and will just mention a few, of which you have no doubt read, in Burma, Newfoundland and Labrador. Back in Labrador an air liner crashed and 11 people, some of them injured, were marooned for several months. When a helicopter was sent to rescue them some of them declared that this was the most beautiful sight in the air that they had ever seen. I hope they were sincere.

Several other rescues have been made, one of the latest being on a very stormy day when the wind was of sufficient force to uproot trees and damage roofs. The police rang up our factory to say that an oil-carrying barge with two men on board was in distress and was starting to disintegrate,

water sweeping over the surface of the barge. We immediately despatched a helicopter with a hoisting sling and in spite of a wind of about 60 m.p.h. and gusty, the helicopter quickly reached the barge and was able to hover 20-25 ft. over it, lower the hoisting sling and take the men off, one after another. The rescue was made as the end of day was approaching and the general consensus of opinion was that these two would certainly not have been able to stay on the damaged barge overnight.

Just when I was ready to leave on the " Queen Elizabeth " the latest information which I received was of another life that had been saved. Here again, during a forest fire, a man became surrounded by flames, and his life was in great danger. He was provided with a " walkie-talkie " radio by which he was able to communicate with someone nearby. A helicopter was sent up and fished him out.

It is difficult to tell you of all such cases but it is interesting to know that in spite of the very young life of the helicopter, so many cases have already been recorded.

Many other cases have been recorded when a helicopter was used recently during a Navy cruise in the Atlantic. In one case the pilot of the helicopter saw the airplane was in difficulties and was actually in the air before the plane crashed. The pilot was injured—disabled—and already sinking, when he grabbed the hoisting sling. The wheels of the helicopter at that time were already down in the water. The life of the man was saved but—and this is an exceptional case—had assistance been delayed for only half a minute, this man would have been lost.

It is a source of much satisfaction to us and a great encouragement to everyone connected with the helicopter industry that lives have been saved in emergencies like these.

Another point is, what can a helicopter do and what is the present performance of a helicopter ? I will mention a few figures, but it is needless to say that the figures will be exceeded very soon by our helicopters as well as by other machines.

Greatest speed (fully loaded)	114 m.p.h.
„ altitude (light)	21,000 ft.
„ altitude (fully loaded)	16,000 ft.
„ load	2,909 lbs.
„ payload	2,500 lbs.
Maximum load	18 men.

The Army have lifted a substantially greater load—at least 600 lbs. more than that of the R-5 helicopter, but the machine would not hover nor take off vertically with this load.

Official longest distance	700 miles.
„ „ duration	10 hours.

Needless to say all these figures are going to be exceeded very soon.

I would like to go over just a few points on the development of the helicopter. I started to built the first helicopter in 1909 and built another in 1910. The first could not fly because of a great number of reasons. I would say because the engine was too heavy and there was not much power. The main thing was I did not have enough knowledge at that time. Later in 1910 I turned my attention to fixed-wing aircraft, built my first aeroplane and climbed into the cockpit and tried to fly it without knowing how to. Quite a problem indeed. However, the aeroplane could fly and even did

so—at least with respect to my ability to stay up. The maximum speed, cruising speed and minimum speed were all just about the same—something which has not been achieved by any other designer!

Later on I built better airplanes, until in 1930 I started building four-engined ships and flying boats in America, but during all this time my main interests were still with helicopters and I still wanted to make one fly. In 1939 we produced our first helicopter. It was of very simple construction, being built of welded steel but was capable of easy adjustment, thereby enabling valuable information to be obtained. This aircraft had a very interesting life of about four years, during which time it was tested extensively. I was the test pilot during the first flight in October, 1939. It had a single main rotor with an anti-torque rotor at the tail. This aircraft was crashed about two months after the first flight as a result of which the cyclic pitch control, which was installed in the first helicopter, was discarded and we went for control by way of auxiliary rotors. We fixed two additional lifting rotors at the rear end, where also was mounted a third rotor for balancing torque and directional control. The operation of both of these lifting rotors in the same direction gave longitudinal control, in the opposite direction gave lateral control. After various experiments, by the end of 1940 the machine was able to stay up for 15 minutes or so. About that time a minor trouble was the subject of a discussion I had with the President of United Aircraft. He had mentioned that the aircraft was flying very well sideways and quite well backwards, but he had not yet seen the machine flying forwards like other aircraft, to which I replied : " Sir, that is a minor engineering problem that we have not yet succeeded in solving."

Later on we arranged to fly forward very well because we found that controlling by means of auxiliary rotors, the auxiliary rotor should not be placed in the slipstream of the main rotor. If they are behind they should be situated above the main rotor. After early trials with auxiliary rotors in front they were placed at the tail and were all right. Rearwards flying of the machine was very successful. However, we decided, in making the next ship, to replace the two rotors by a combination which presented a more or less tandem rotor helicopter with one large and one small rotor besides a small tail rotor. This craft gave very satisfactory results and could gradually be accelerated to a higher speed, which was of the order of 75 m.p.h.

Early in 1942 we had a two-seater helicopter for the Army ready, with full cyclic-pitch control. This machine, the R-4, is well known in this country and has given very satisfactory results. It was flown for the first time in February, 1942, and subsequently made the journey from Bridgeport, Conn., to Dayton, Ohio, in a somewhat roundabout route in order not to meet high mountains. There were all manner of very interesting experiences during the visit and I would say we attracted a great amount of attention.

On arrival at Dayton the helicopter flew over the hangar, stopped in the air, flew backwards, stopped in the air in front of the hangar and then landed. A mechanic came out of the hangar and said : " I don't know whether I'm drunk or crazy ! "

The R-4 was designed only as a prototype for limited flying but it has done a large amount of practical work, and a number of successful missions.

Some of the R-4's are still flying, although this craft had been designed mainly on early experience.

After this several helicopters have been produced. The R-6, similar to the R-4, but more refined. The R-5, with 450 h.p. engine and planned originally as a two-seater but later transformed into a four-seater. This is a very successful helicopter, capable of rendering services like no other airplane.

Now I would like to show just a few examples about the job of an engineer in designing the helicopter and particularly during the pioneering period. It was a most interesting work and quite a difficult one. There was no knowledge available, and no reliable literature. The aviation designer of 15 years ago had a considerable amount of reliable information on which he could base his designs, but the helicopter designer had practically nothing.

In the helicopter we have a rotor which turns round but nobody knows what happens to the rotor. We felt that this was wrong—we must study and learn what happened to the rotor. So what we did was to observe it first with the aid of a camera. Also we tried to observe the blades by means of stroboscopic effects, and one very dark night the R.4 helicopter was hovering about 30 ft. from the ground, and lighted from the ground, with the camera alongside the blades. I was sitting on the undercarriage watching the blades and it was very unpleasant to see them apparently stationary in the interrupted light!

We made a considerable amount of such studies, and now, once the stresses are established the rest is easy. We can take the blade, reproduce the stress by bending, subject the blade to 20 million oscillations and determine that the blade is safe and will have an indefinite life. If it is unsatisfactory it will fail much earlier than that. This is now an established method which is very useful.

The latest machine is the S-52, a two-seater, which has metal blades and is comparatively cheaper to produce; for instance, it has been possible to introduce a standard automobile clutch. There have been many problems in developing the metal blades and much work has also been done to measure the stresses by means of strain gauges. These gauges are very useful,

Sikorsky R-4 in hovering flight. Mr. Igor Sikorsky converses with crew.

Sikorsky VS-300 and Sikorsky XR-4.

but sometimes I would say they can play jokes. In our first tests we found stresses which were much bigger than was expected and we could not believe them. Later we found it so happened that the amplitude and frequency of vibrations made the needle in an electric oscillograph system installed in this machine jump up and down, corresponding with the frequencies in the blades. Instead of marking accurately, it marked perhaps half an inch or perhaps two feet too high. When this was corrected the stresses were found to be what we had expected.

I would like to make one more point which is very necessary to mention and that is the absolute accuracy of the control of the helicopter. I believe that a helicopter can be made with a control as perfect as any other system of control. A most interesting experiment was carried out by Cmdr. Erickson of the U.S. Navy with an R-4 helicopter. The machine was on floats and a scheme was devised whereby the floats were dropped once the aircraft was in the air. For landing a six-inch ring was mounted on the float gear, and a pointer fixed to the helicopter. When Cmdr. Erickson sighted the pointer in the centre of the ring, although he could not see the landing space, he could drop down accurately on to the attachments of the float gear.

Finally, in the future we can expect much larger helicopters and I do not think we should be too dogmatic about the configurations. The future will show which one is the best. It is possible that future helicopters will be jet-driven, or power driven, not through the shaft, but through the tip of the blade.

The future of the helicopter is immense and later the craft will be a very familiar sight in the air to everyone. It will also be capable of rendering a great number of services which no other craft can render, and can be described as the greatest friend in need in the case of an emergency.

In reply to a question by Dr. Thurston on de-icing for helicopters, Mr. Sikorsky said :

I believe that with respect to the airplane the question is too well known and I am not sufficiently informed with details to speak on it. I shall be very glad to give you information about helicopters which I believe to be correct. It has never been possible to accumulate enough ice to cause any trouble under ordinary conditions. Extensive tests were conducted with a helicopter stationary on top of a mountain when conditions were very bad. The helicopter was stationed there for two months, with instructions to pick up the very worst conditions. It was found that ice would accumulate within a few minutes to such an extent that the helicopter in flight would have been in very serious trouble.

Tests are being made to counteract icing by United Aircraft, using paste.

Princeton University have made very extensive tests, using heat applicances, with electric conductors through the blades. The best results have been obtained by sending current in pulsating waves—the current is applied to one portion of the blade, taken away and re-applied to another portion, and so on. It has been found possible to de-ice the R-6 helicopter by using 2 k.w., but with a slightly larger helicopter probably 3-3½ k.w. would be required.

DR. J. A. J. BENNETT.

Mr. Chairman, members of the Helicopter Association and guests, I am sure that we are all deeply indebted to Mr. Igor Sikorsky for coming here this evening and telling us about his recent helicopter developments. It is strange to recall that only a few years ago I had the privilege of watching the initial tests of the VS-300 at Bridgeport ; the helicopter was known as " Igor's folly," a designation given to it by those who did not believe in the future of rotary wing aircraft. Today, however, the helicopter is recognised throughout the world as an outstanding achievement in aeronautics and we have the greatest respect for the genius of the man who brought this about. We congratulate Mr. Sikorsky on his successful family of helicopters and I have great pleasure in proposing a vote of thanks to him for a most interesting and enjoyable talk.

Sikorsky S-52.

Some Work with Rotating-Wing Aircraft *

By O. L. L. FITZWILLIAMS, B.A.

A lecture illustrated with slides and delivered before the Helicopter Association of Great Britain on Saturday, 25th October, 1947, at Manson House, 26, Portland Place, London, W.1.

H. A. MARSH. A.F.C., A.F.R.Ae.S., IN THE CHAIR

INTRODUCTION BY THE CHAIRMAN.

Ladies and Gentlemen,

It is my privilege to introduce to you today MR. FITZWILLIAMS, whose subject is " Some work with Rotating Wing Aircraft."

MR. FITZWILLIAMS is a founder member of the Helicopter Association and a member of our Council and has been engaged on various aspects of rotating wing development over the past nine years, first with Mr. PULLIN at Messrs. G. & J. Weir Ltd., and later with Mr. HAFNER at the Ministry of Supply. He is now Helicopter Engineer of the Westland Aircraft Company.

During the latter part of his time with the Ministry he was in charge of the rotating wing section of the Airborne Forces Experimental Establishment at Beaulieu. I understand that this period supplies the bulk of the material for his talk and I feel sure we shall find it both interesting and entertaining.

On behalf of the Association I extend a cordial welcome to our guests.

MR. O. L. L. FITZWILLIAMS, B.A.

Mr. Chairman, Ladies and Gentlemen,

My talk this afternoon consists of brief descriptions of two rotating-wing aircraft produced in Germany during the war, followed by a more lengthy discussion on the engine-off landing of helicopters, and some concluding remarks about the work which we now have in hand at Westland Aircraft.

We still have a great deal to do before completing our conversion of the S-51 helicopter and this work cannot yet be discussed in detail, but by the middle of next year I hope that we will be ready with a full description

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of the British S-51 and of its possibilities for future development. In the meantime the assortment of subjects which I have chosen for my talk this afternoon may be regarded as a kind of hors d'oeuvre before the more substantial dishes which may be expected in future, and I hope you will find it sufficiently interesting for a start.

FOCKE-ACHGELIS Fa 330.

The first of the German aircraft which I am going to discuss is the Focke-Achgelis Fa 330—which is the proper name for the German autogyro kite for submarines. The kite is quite well known now, although few people

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Fig. 1. Fa 330 Kite—without blades.

have actually seen it fly, but information about it became available only after the war and you can imagine our surprise when the contraption arrived at A.F.E.E. in August, 1944. With it were some odd blades and tail surfaces and a note, saying that it had been found on a captured submarine and asking us to put it together, find out how it worked and, if possible, fly it. The photograph shows the fuselage unfolded and with the tail surfaces stuck on, and it did not look very encouraging (Fig. 1).

The fuselage was in a very bad state of repair and there was a large bullet hole through the main upright member and the control rod which this member contains. The blades were also in bad condition, and of the six received one was bent at the root while the others were full of holes and set at all sorts of angles. The wires hanging down

from the head are inter-blade bracing cables and are shown in their proper position, with the blades mounted, in Fig. 2, which was taken after the whole kite had been repaired and re-conditioned.

Although later flight tests showed the kite to be as well designed aerodynamically as in detail, it was at first regarded with great suspicion and I remember that we had quite unfounded doubts as to whether it had ever been flown at all. Moreover Mr Hafner and almost all of the rotary wing staff of the A.F.E.E. decamped to Bristol at this point, leaving Mr. Leonard Liscombe and myself with the single helpful suggestion about flying the kite from a trailer towed by a jeep, and a large number of derisive remarks

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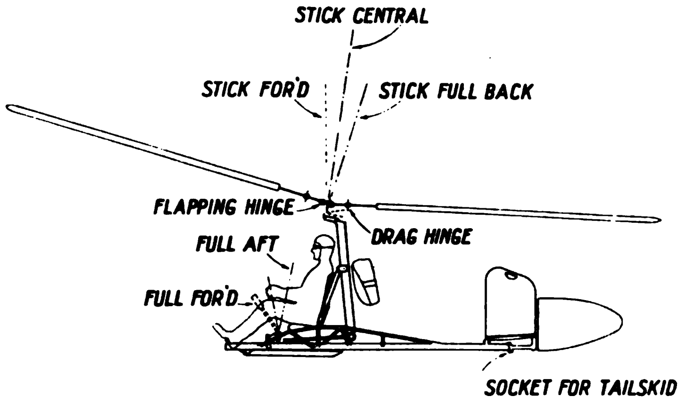
Fig. 2. Fa 330 Kite—Blade Assembly.

about the possibility of our doing so without breaking at least the kite and probably the pilot as well.

The general arrangement of the kite is illustrated in Fig. 3. Its detail design has often been described but it is so ingenious that I hope I may be forgiven for briefly mentioning again some of its outstanding points. For stowage purposes the blades and tail surfaces are quickly detached and the back of the seat is unclipped from the main upright member so that this can be folded back over the tail. The seat is then folded back and also the control stick. Finally the landing rails are folded close in to the sides of the fuselage, which can then be inserted into the cylindrical watertight container in which it is stowed on the deck of the submarine. The blades and tail surfaces are stowed together in another container.

The most spectacular feature of the kite is that in addition to the ordinary tow cable quick-release there is a handle beside the pilot's head which he

can pull if attacked in the air. The consequences of doing this are that the tow cable is released and at the same time the whole rotor flies off, pulling with it the top of a parachute to which it is attached by a breaking-tie. The parachute is normally stowed in the dish-like tray behind the main upright and its rigging lines are attached to a point on the pilot's harness, so that when the parachute is open it supports the pilot who is still attached to the



GENERAL ARRANGEMENT OF FA 330, ROTARY WING KITE.

Fig. 3.

rest of the kite by means of his safety belt. When this belt is undone the remaining structure falls away and the pilot is then free to drown in a conventional manner.

Certain features of the kite gave rise to considerable doubts as to the proper method of handling it—for instance, the fuselage is fitted with a socket for a tailskid and it was some time before we realised that this has nothing to do with operation from a submarine but is used in conjunction with a very tall undercarriage developed for training purposes on land.

Also we knew nothing of the stability characteristics of kites, except that model autogyro kites are often highly unstable, and if it had been difficult to fly it would have been most unpleasant to attempt to take off and land on a relatively narrow trailer being towed down a runway, which was the only method open to us without extensive alterations to the kite.

Thus the first problem was to find out something about the behaviour of rotary-wing kites in general and of this one in particular before embarking on a set of flight trials which might wreck the only available example. There are probably much more elegant methods of examining this problem than the one I am about to describe but our rather crude method, although far from being an exact calculation, does give a fairly comprehensive and easily understood picture of the behaviour of rotary-wing kites in general—as well as results which are of the right order as regards the magnitude of the forces acting on them.

To begin with there are only three major forces acting on a kite, namely the Total Air Force, the Tow Cable Pull, and the Weight, as shown in Fig. 4.

The Total Air Force is made up of the Rotor Thrust, which can be assumed in this case to act through the rotor centre at right angles to the rotor, and the Fuselage Drag which is horizontal and which we assumed to act through the C.G. The weight acts vertically through the C.G. and the moment effect of the tail lift can be included with reasonable accuracy by assuming the C.G. to be displaced a suitable distance from its true position, neglecting the effect of the tail lift on the linear balance of the major forces. The Tow Cable Pull, of course, acts through the Quick-Release attachment of the cable to the fuselage.

We know the positions of the rotor centre, C.G. and quick-release point in the fuselage so that if we can find some means of determining the magnitude and inclination of the major forces acting in a given condition of flight, we can soon determine the corresponding fuselage attitude, stick position, etc., by a trial and error process. The trial and error part is quite simply done with the aid of a transparent copy of the dotted parts of Fig. 4, which is moved about over a series of trial force diagrams until the position of equilibrium is found. Alternatively, we can first assume a given fuselage attitude and stick position—the latter gives the inclination of the rotor thrust relative to the fuselage when a small correction is made for flapping—and then proceed to determine the wind speed at which equilibrium occurs.

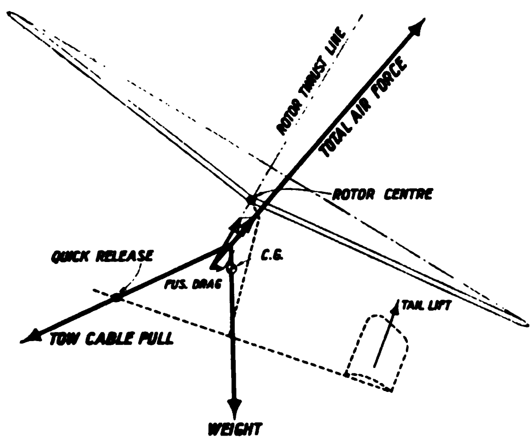
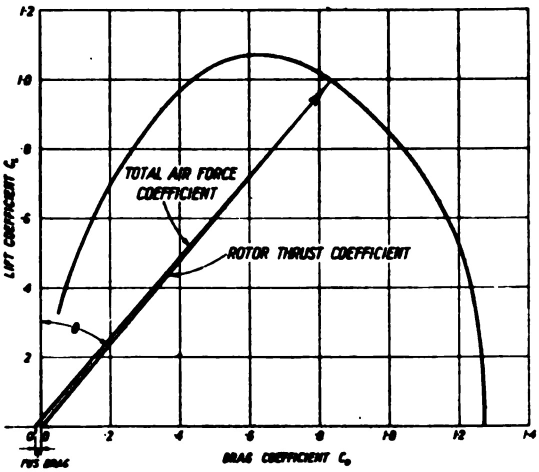


Fig. 4.

FORCES ACTING ON KITE.

This process is apt to be tedious but it is very easy if we have some simple means of obtaining the magnitude and inclination of the major forces. In casting about for something of this sort, we came across test results giving the polar force co-efficient diagrams for the C.30 autogyro rotor and for Mr. HAFNER's small Rotachute rotor and these rotors were sufficiently similar to each other and to the kite rotor to justify us in taking a mean curve as a suitable basis for our estimates.

This curve, which is shown in Fig. 5, indicates a typical relation between the Lift and Drag Co-efficients of a gyroplane rotor and is very convenient for our purpose, because having assumed that the rotor thrust is always perpedicular to the rotor, it follows that if the rotor is inclined backwards



POLAR FORCE COEFFICIENT DIAGRAM FOR KITE

at an angle of θ then the rotor thrust is also inclined backwards at the same angle and the magnitude of its co-efficient can be read direct from the diagram.

Fig. 5.

Moreover, since the fuselage drag is always horizontal, its co-efficient, based on disc area like the others (the diameter of the rotor is 24 ft.), can be set off to the left as shown, so that for a backward inclination of the rotor we have immediately the backward inclination and magnitude of the Total Air Force co-efficient measured from the new origin 0′. The fuselage drag actually is so small that in most cases it could be neglected.

Knowing the inclination and magnitude of the rotor thrust and Total Air Force for any condition of flight, and also the magnitude of the weight acting downwards, we only require to know the magnitude and direction of the Tow Cable Pull in order to draw the complete force diagram. But we can find this out quite easily if we take 0′ as the origin for a new graph on which we can re-plot the curve shown in Fig. 5, this time not in terms of the co-efficients which are independent of wind speed but in terms of actual forces for a number of different wind speeds shown in Fig. 6.

Fig. 6 is, then, a polar diagram of actual forces so that if we take a wind speed of, say, 39 ft./sec. and consider the Total Air Force to be inclined backwards along, say, 0′A, we can immediately complete the force triangle by marking off a vertical distance 0′B equal to the weight so that BA now gives the magnitude and inclination of the Tow Cable Pull.

Two rather important things are immediately noticeable from Fig. 6. Firstly, it is obvious that if the kite is flown with the stick far forward, the rotor thrust will be only slightly inclined backwards. The forces acting on the kite are then defined by a point on the lower left hand part of the curve for the particular wind speed. Also, as the stick is brought back, the point defining the forces acting on the kite moves from left to right along the given curve.

Therefore, as the stick is brought back, the tow cable, which may have started at an inclination even below the horizontal, gradually rises until it reaches the angle defined by a point such as C, where its upward inclination is a maximum for the given wind speed. It is not, of course, surprising

that at a given wind speed there should be a particular stick position giving the maximum kiting performance, but it is rather disturbing for a pilot to contemplate flying an aircraft which, towed at a constant airspeed, will rise on the tow cable when the stick is pulled back part of the way and fall at ever-increasing speed when the stick is pulled back the rest of the way. Especially when flying on a short tow cable you can imagine the embarrassment of a pilot who finds himself descending with no means of knowing whether he should push the stick forward or pull it back or just sit and wait until the wind freshens.

Fig. 6 also illustrates the fact that whereas the rotor of a normal rotary wing glider supports only the weight of the aircraft, that of a kite supports a large part of the tow cable pull as well. Moreover, the forces which could be developed by the rotor at quite ordinary wind speeds appeared to be far larger than the fuselage of the Fa 330 was designed to withstand.

To investigate these points further it was decided to work out not only the take-off and landing behaviour, in which the stick was found to be roughly central with the fuselage in a very tail-down attitude, but also to examine the kite's behaviour with the stick hard back, in which condition the maximum rotor forces and instability could be expected.

We have already noticed that as the stick is pulled back, the point defining the forces acting on the kite moves from left to right along the curve for that particular wind speed. At high wind speeds, when the tow cable is pulling the kite's nose strongly downwards, we find that there is a limit to the backward inclination of the rotor even with the stick hard back, so that the force-point can only move a certain distance along each curve. If these limiting positions are joined up we find there is a definite limit to the forces which can be imposed on the kite and a typical limit of this kind is shown by the thick curve in the upper part of the diagram. This curve is kinked because it includes an allowance for the lift of the tailplane, which is assumed to stall at the angle indicated by the kink.

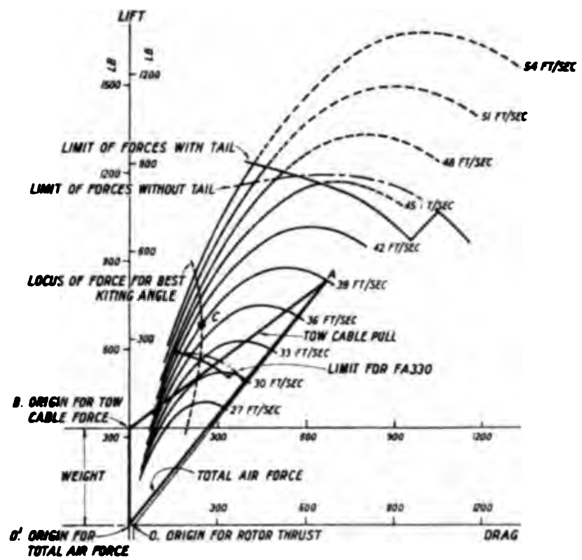


Fig. 6.

POLAR DIAGRAM FOR KITE TRIANGLE OF FORCES.

At low wind speeds the forces on the kite do not reach the limit curve so that the tow cable angle will still increase when the stick is pulled back part of the way, and decrease again when the stick is pulled back the rest of the way. If the stick was actually pulled hard back the result would be a very unpleasant tail slide.

At higher speeds, where the forces on the kite reach the limit curve, a momentary equilibrium could be obtained, but the condition would be unstable because the limit curve is reached after the inclination of the tow cable has passed its maximum. In this condition, if the kite is disturbed in such a way that its nose is pulled down slightly, the change in attitude will correspond to a larger inclination of the tow cable so that the kite will start to move forward against the wind and at the same time the rotor thrust and speed will both drop off. After a short interval, if the pilot keeps the stick hard back, the nose will rise again and the kite will drift backwards with the wind while the rotor thrust and speed build up again to an amount which will overshoot the normal force limit and the nose will be sharply pulled down again so that the unstable movement will build up. Except on a general basis I have not examined this oscillation very carefully, but anyone who has played with model autogyro kites will recognise it and I think you will agree that it does not represent the best condition for calm observation of enemy shipping.

Owing to an oversight in our preliminary examination, we thought at first that the force limit in the upper part of this diagram represented the characteristics of the Fa 330 and the huge forces and unpleasant behaviour which it indicates are not only a warning to designers of future kites but they also caused us to do the first tests in a very gingerly manner with the kite securely tied down. However, these tests immediately showed that the Fa 330 is really a very tame affair and on looking for an explanation we found that Dr. KLAGES, the designer, had very carefully arranged the back stop on the control stick so that the flight characteristics are actually those shown by the limit curve in the middle of the diagram. This curve indicates that, in almost any wind in which the kite can fly, it is stable fore and aft and has its maximum performance with the stick hard back. Also in this condition the rotor thrust and speed are substantially constant irrespective of wind speed. These characteristics were confirmed in flight tests, and with S./Ldr. KRONFELD at the controls the kite soon showed itself to be everything a submarine commander could wish for as an observation platform.

The kite required fairly dextrous handling when flown on a short tow cable, but was quite docile on the longest rope we could manage (22 ft.) and KRONFELD was able to let it fly hands-off for appreciable periods on this length of cable in spite of its slight lateral instability.

I have here an illustration showing KRONFELD, in his usual role of intrepid birdman, braving the elements in this curious contraption (Fig. 7).

It is doubtful if rotary wing kites will ever be a serious requirement likely to weigh heavily on the members of this Association, but the effort spent on this one may not have been wasted. Not long before I left Beaulieu we received from Australia a request for advice on the possibility of operating these kites from fishing vessels, for spotting shoals of fish. Although a kite could be used for this purpose I am inclined to think it would be more of a trouble than a help. But the ease with which it could be landed and

Fig. 7. Kronfeld testing Fa 330 on short tow cable.

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launched, from a tiny platform only a few feet square and in all sorts of weather, does suggest that for applications of this sort there would be some benefit in developing a kind of combination kite and helicopter as shown diagrammatically in Fig. 8.

The main requirement of such an aircraft would be the ability to develop a lift substantially greater than its own weight. This is, of course, easily done even without an engine provided there is ample wind, and it is necessary in order to keep the tow cable tight when the platform is moving up and down. The most difficult case would be when there is a heavy swell in the calm air.

I believe it would not be very difficult to meet this requirement and air observation would then be possible even in calm weather, while in windy weather the aircraft could sit for hours on the end of the cable at no cost at all. Moreover it could always start its engine and drop the cable at will to go cruising about under its own power.

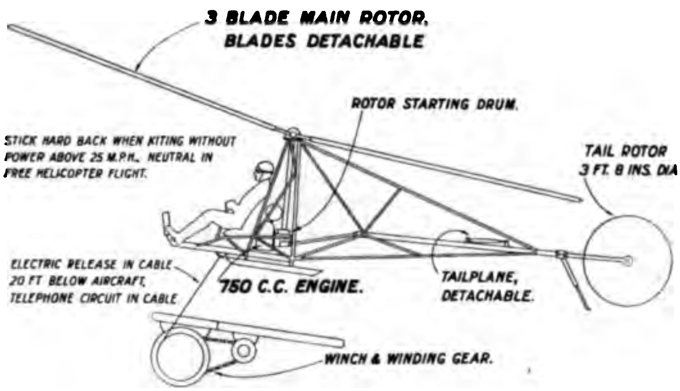

Fig. 8

SUGGESTED COMBINED KITE AND HELICOPTER.

I picture the tiny landing platform, with its attached winch, as projecting from the side of the ship so that when the aircraft wished to hook on again it could drift slowly backwards low down over the platform, with about 20 ft. of cable dangling from its nose. It would hover while an operator on the platform hitched the dangling cable on to the main tow rope and it would then back up until the cable became tight. The power could be shut off as the aircraft began to kite and finally to rise up on the tow cable for a further spell of cheap spotting.

Observation of the kite's behaviour leads me to suppose that landing and take-off with this arrangement would be quite a practical business on a fishing vessel and it may be that it could be developed for more general application to helicopter's operating at sea.

Focke-Achgelis Fa 223.

I would like now to tell you something about another aircraft which came to us at Beaulieu from the same stable as the kite. This was the big Focke-Achgelis F.a.223 helicopter shown in Fig. 9.

The prototype was built in Bremen in 1940 and it was not only highly successful as a helicopter but it also met requirements for anti-submarine patrol, armed reconnaissance, air sea rescue, cargo transport, etc., which could be met by very few of our present-day helicopters. Moreover it did this at a time when other helicopters were either on the drawing board or else in a strictly laboratory stage, and it was not even considered to be an experimental aircraft to any important extent, since its design is very firmly based on that of the smaller FW.61 helicopters which had been flying successfully since 1937.

Thirty F.a.223's were ordered by the German Air Ministry but construction work was limited to twenty-five, of which the majority were destroyed by bombing in various stages of manufacture. Only three remained serviceable when the war ended and one of these was destroyed by its pilot. The remaining two were delivered to the Americans at Ainring in May, 1945, and one, the 14th production aircraft, was subsequently flown

Fig. 9. Fa 223 Helicopter.

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by its German crew, via Paris, to the A.F.E.E. at Beaulieu, where it arrived in September, 1945, having performed the first crossing of the English Channel by a helicopter.

Fig. 9 gives a good view of the arrangement of the F.a.223 and you can see the cooling air intake grill just forward, and the outlet slit just aft, of the 1,000 h.p. Bramo Fafnir engine, which is mounted, facing forwards, in the centre section of the fuselage. The rotors are driven by long transmission shafts connecting a right-angle drive on the front of the engine to double-reduction gears in each rotor head.

The undercarriage struts and the two main top members of each outrigger were round tubes but the remaining members were of roughly streamline section, and although a good deal of power is required to drag all this bridgework through the air, the F.a.223 could slip along at 95 knots when in a hurry and cruised normally at 65 knots. The fuselage provides accommodation for pilot and observer in the nose and for a navigator and one other crew member in a separate compartment behind the cockpit.

The undercarriage is interesting because it serves two quite distinct purposes. Normally the fuselage is horizontal and the aircraft sits on its main and nose wheels with the main wheels behind the C.G., but if the tail is pulled down it will rest equally happily on the tailskid and the main wheels, which are then in front of the C.G. In this attitude the rotors have quite a large angle of incidence of 12° relative to the ground. In autorotation the aircraft would land like this and although its engine-off landing speed is fairly high—of the order of 35-40 knots—the huge drag of the inclined rotors results in quite a short landing run.

Fore and aft control is by normal blade feathering, which tilts both rotors forwards or backwards together. Yawing control is obtained in hovering flight by tilting one rotor forward while the other is tilted back, but the pedals also operate the rudder and this does most of the work in forward flight, thus avoiding the adverse rolling moment which results from differential tilting of the rotors in forward flight, when they act more like ailerons than as a yawing control. When the aircraft was turned in hovering flight by application of rudder control the turning movement resulted in a large increase of effective disc area so that the machine climbed quite rapidly without any increase of power. This corresponds to the epicyclic arrangement of rotors mentioned by Dr. Bennett in his lecture.

Lateral control is obtained by increasing the lift of one rotor and decreasing the lift of the other, but there is no means of increasing or decreasing the lift of both together except by the rather indirect means of changing the throttle setting and waiting for the rotors to speed up or slow down. This control is sluggish and requires much foresight when manoeuvring in gusty weather near the ground, although because of its symmetrical arrangement and simplified controls the F.a.223 was apparently easier to learn to fly in the initial stages than most of our present helicopters.

In the fore and aft direction it had the same instability which is familiar, in all directions, to pilots of single-rotor helicopters, and in the few flights I had as a passenger I did not notice that the large tailplane resulted in any marked improvement in forward flight, at any rate at moderate speeds. On the other hand it was quite strongly stable about the rolling axis so that in calm air an angular disturbance about this axis, or a lateral movement of the aircraft, would soon be damped out if the controls were held central.

Watching the behaviour of the aircraft one was, however, impressed by the fact that stability of this kind does not necessarily mean that the aircraft has any tendency to keep still in gusty weather. On the contrary, the rotors were very sensitive to changes in airflow, and in gusty air they bobbed up and down in a quite impressive manner, requiring sharp control movements to keep the aircraft level.

Under operational conditions the F.a.223 was flown at an all-up weight of 9,500 lb., which included 2,500 lb. of disposable load, a proportion which compares favourably with most present helicopters. On a weight per horse power basis it was, however, a rather poor performer, largely because of its very high disc-loading which, at this weight, was 3.9 lb./ft.^{2}. Nevertheless, I imagine the KELLETT XR10 and the MCDONNELL, both of about the same power as the F.a.223, are the only present-day helicopters carrying a normal disposable load approaching 2,500 lb., though several others could lift this weight as an overload with the help of a breath of wind. The Focke, of course, could also lift an overload, flying with a disposed load of 4,000 lb., including the whole centre section, with engine, of another F.a.223, the weight on the end of the cable being 2,820 lb.

Although the mean blade pitch of the rotors was fixed in helicopter flight the pitch could be reduced to ensure autorotation. To do this the pilot could operate a two-position lever which was connected to a highly amusing mechanism which had ramifications in all parts of the aircraft. When the lever was raised it caused the engine clutch to be engaged by a hydraulic ram which also set the rotor blades to helicopter pitch. When the lever was lowered the clutch was disengaged and the rotor blades returned at a controlled rate to the autorotative pitch. In addition to clutch and pitch operation the mechanism changed the tailplane incidence for each condition, operated a valve allowing lubricating oil to be pumped by the engine to the rotor heads in helicopter flight, and automatically closed and locked the throttle when changing the autorotative flight. The mechanism operated automatically in the emergencies of engine-failure, oil pressure failure, transmission breakage, or operation of the pre-loaded free-wheel mechanisms in the hubs. Also a governor-operated cut-out in the ignition system, intended to protect the engine when suddenly de-clutched, could mistakenly operate the mechanism if the rotors were over-speeded as could happen in manoeuvres near the ceiling of the aircraft when carrying a heavy load. Further complications were necessary to make taxying possible with the rotors turning above the critical change speed.

Once the mechanism had operated, even voluntarily, it was impossible to regain the helicopter condition in flight and a glide landing was necessary. In fact, with the high disc loading of this aircraft and the absence of any control over the blade pitch, a glide landing was essential and if there was not enough height for this purpose the operation of this so-called safety mechanism would dump the aircraft as a heap of wreckage on to the ground.

This actually happened, at about 60-70 ft. above the ground, shortly after the machine arrived at Beaulieu, and I was among those who were sitting in it at the time. In consequence I have a strong prejudice against trick gadgets in helicopter control systems and also a rooted objection to helicopters, however light their disc loadings, which do not allow the pilot direct manual control over the blade pitch in order to cushion a forced landing.

Before leaving the F.a.223 I would like to call your attention to the extent of the equipment fitted to this 1939 design. It had a good working position for the navigator and full radio and instrumentation, including an electric artificial horizon, also dual controls could be fitted.

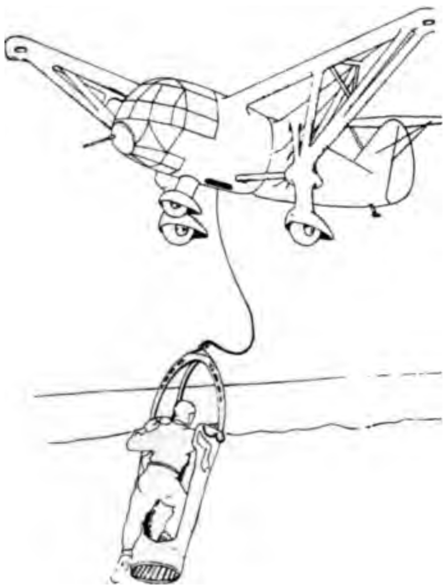

Fig. 10.
Fa 223—Method of air/sea rescue.

A machine gun could be fitted in a standard ring in the nose, with the gunner in a prone position on the padded floor, and two 250 K.G. bombs could be carried on racks beneath the fuselage. Also a standard 4-man emergency dinghy, inflatable from the cockpit, was stowed in the upper part of the rear fuselage.

Of the specialized fittings, you have already seen how external loads were lifted on a cable suspended beneath the fuselage. To aid the pilot in landing suspended loads at night, the aircraft examined at Beaulieu was fitted with a radio altimeter. A powerful landing light was also fitted in the nose and this was rotatable about its horizontal axis by an electric motor.

Finally, I think we can still learn some lessons from the Air-Sea Rescue equipment fitted to this helicopter. Fig. 10 shows the special rescue bucket floating with its rim level with the water and with a large opening in one side, into which even an injured man can swim easily. Once in the bucket the injured man stands on an open grid floor, which allows the water to escape when the bucket is lifted. A safety strap can be fastened across the opening and it was originally intended to provide intercommunication between the rescued person and the pilot, although I do not think this

was ever fitted. Fig. 11 shows the way in which the rescue bucket could be hoisted through a hole in the cabin floor, right into the aircraft, so that the man can safely be taken out of it.

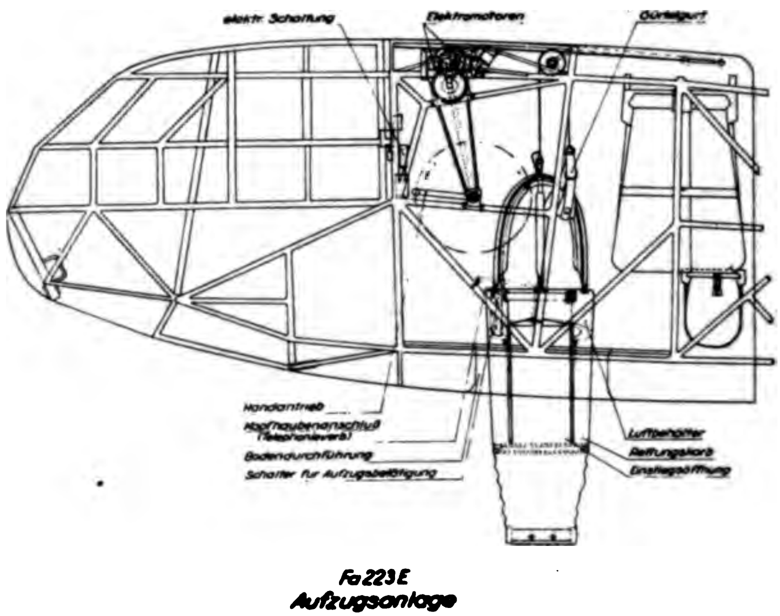

Fig. 11. Fa 223—Arrangement of air/sea rescue apparatus.

The F.a.223 represents the first successful attempt to develop an operationally useful helicopter, and I think you will agree that considering the time and circumstances of this development, it was a very remarkable achievement.

ENGINE-OFF LANDING.

From these descriptions of two aircraft, which are of interest mainly for historical reasons, I turn now to a discussion of the engine-off landing of helicopters. This is an aspect of helicopter flight which has a particular fascination for me because I have had the good fortune to take part in certain experiments connected with it and I believe that a study of it leads to important conclusions with respect to the possible use of helicopters on a very large scale.

There is still a good deal of argument about engine-off landings and in discussing them with all sorts of people I find a diversity of views and experience which is extraordinary, considering the length of time that helicopters have been in operation. The subject is made up of a number of very simple considerations which most people consider to be obvious but, probably for this reason, nobody seems to have bothered to analyse them in detail or to set them out in a logical sequence.

Our present confusion arises partly because the requirements of an engine-off landing have not received adequate attention in the design of

our first generation of helicopters, and partly because very few pilots have been trained *ab initio* on helicopters. Thus the early pilots have found that they can pull off forced landings in a helicopter with the aid of techniques previously learnt from the aeroplane and the autogiro. These techniques are familiar and their successful modification to suit the helicopter has enabled us to answer a lot of awkward questions about what happens when the engine stops, but when one watches the modern pupil being taught to practice engine-off landings by doing violent flare-outs or high speed dives followed by long floats over the ground one cannot help thinking that an essential screw somewhere wants tightening.

In practice these techniques work remarkably well, but they are nowhere near what is required before the helicopter can be considered suitable for large scale use as a common means of personal transport. Also their familiarity and apparent naturalness have led to their limitations being accepted as inherent limitations of the helicopter and it is now up to the designer to expose this fallacy by providing helicopters which, in the event of engine failure, can be landed as helicopters instead of as imitation aeroplanes or autogiros.

Although opinion among designers may not be unanimous on this point, I believe the facts are sufficiently obvious to ensure an early improvement in the case with which engine-off landings can be made, but in general it will take some time to produce new helicopters and to modify existing ones to meet the new requirements. In the meantime, before our confusion gets worse confounded by current training programmes, I think there is a need to set out and examine the considerations governing the performance of an engine-off landing, so that we can at least have a common basis for discussion of our present practice and a common understanding of the changes which may shortly be expected.

To begin with, the most obvious thing about any method of performing an engine-off landing is that its primary purpose is to eliminate the downward velocity of the approach glide. Therefore, during some part of the landing manoeuvre, the vertical component of the Total Air Force acting on the aircraft must exceed the weight for long enough to allow the downward velocity to vanish.

During the approach glide the aircraft is in equilibrium at a constant speed so that the Total Air Force acting on its vertical and equal to the weight and the energy required to produce this force is supplied by the potential energy which the aircraft is steadily losing by virtue of its descent. The supply of potential energy is, however, cut off at the same time as the descent is arrested, while the force required to do this is at the same time greater than that which was steadily maintained in the approach glide. The necessary considerable supply of energy must therefore be tapped from some other source and in an engine-off landing the only other sources are the kinetic energy which the helicopter possesses by virtue of its speed along the glide path and the kinetic energy stored in the rotors by virtue of their anular velocity. It therefore follows that while the downward velocity of a helicopter is being arrested there will be a reduction of the speed along the flight path or of the angular velocity of the rotors or of both and these three ways of using the kinetic energy which is available correspond to the three types of possible engine-off landings.

The considerations which govern the manner in which the kinetic energy is used are illustrated in Fig. 12. This illustration may look rather complicated at first, but I think it will be quite easily followed if we start with the thick arrow in the upper part of the illustration, which is a polar diagram similar to those we have discussed in connection with the Kite. The thick arrow represents the motion of a helicopter in steady flight, because its length indicates the speed of the helicopter, and its downward inclination is the actual slope of the glide path, since you will notice that the horizontal and vertical scales inside the border of the diagram are marked off identically in ft./sec.

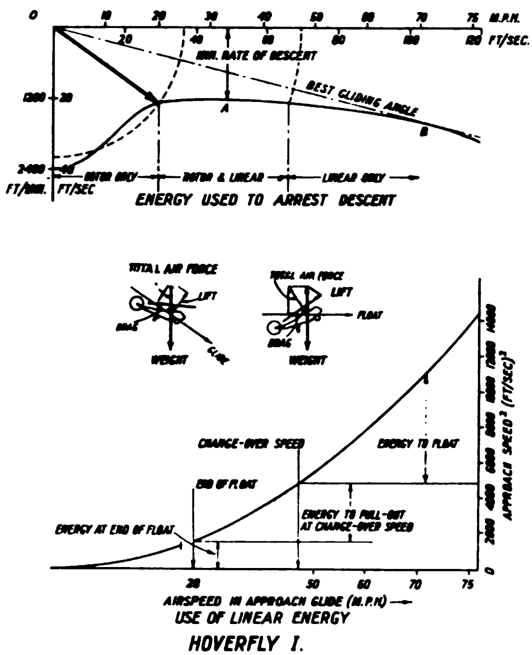

Fig. 12

The arrow rests on a curve, which represents approximately the glide performance of the Hoverfly I. (Sikorsky R-4b) helicopter, and you will notice that if the tip of the arrow were moved from left to right along the curve the length of the arrow would increase and its inclination would get less until we arrive at the point A where the arrow would indicate the gliding angle and flight path speed corresponding to the minimum rate of descent. After this the arrow would get rapidly longer for small changes in the gliding angle until, at B, it would become tangent to the curve and would then indicate the flight path speed for Best Gliding Angle, which occurs near the top of the speed range for the Hoverfly I.

Now, if it desired to eliminate the downward velocity of the approach glide by means of the kinetic energy of forward motion alone, the helicopter must be brought in at a fast glide and the rotor incidence must then be increased beyond the amount which is correct for steady flight. The rotor will then produce an excess thrust and the aircraft will commence to do a normal pull-out. Also the speed of the aircraft will fall during the pull-out and the rotor incidence relative to the flight path will have to be continually

increased so that for each speed it is always more than the amount which would be correct for steady flight. In this way the kinetic energy of forward motion is exchanged for the temporary excess thrust required to perform a pull-out and the result is that, in general, the downward velocity has been eliminated at the expense of forward speed.

If we consider a helicopter which is gliding so fast that the arrow tip is resting on B, then if the rotor incidence is increased by a small amount and the aircraft is subsequently allowed to settle down in steady flight, it will do so in a condition indicated by an arrow resting on some such point as A, and the arrow will then be much shorter than before, indicating that a small increase of rotor incidence corresponds to a considerable loss of speed in steady flight and to a much more considerable loss of kinetic energy since the initial speed was high and the kinetic energy is a function of the square of the speed.

So long as a small increase in rotor incidence corresponds to a substantial loss of kinetic energy, a pull-out can at least be started, but consider the thick arrow in its present position. Here even a large increase in incidence corresponds to only a small change in speed and a negligible change in kinetic energy since the initial speed is low. Even if the rotor were suddenly tipped up at right-angles to the flight path all that would happen would be that the arrow would swing down to indicate vertical descent and then it would be too short to reach the curve until the helicopter had settled down to a steady flight in the new condition.

To measure the length of the arrow in this diagram it is necessary to swing it on to one or other of the scales. If it is swung up to the top scale it can be seen that its length in the position shown corresponds to a glide approach at an indicated airspeed of 25 m.p.h. in the Hoverfly I. and it is clear that in these conditions the kinetic energy of forward motion is, for practical purposes, exhausted so that no sort of pull-out is possible from an approach glide at or below this speed. In fact, for the Hoverfly I., there is no condition of steady gliding flight corresponding to an airspeed of less than about 23 m.p.h., although this is not indicated by an ordinary A.S.I., because the pitot tube is usually horizontal so that it does not register flight path speeds in steep descents.

In engine-off landings from approach glides as steep as that indicated by the arrow, the elimination of downward velocity is entirely dependent on the use of the collective pitch control as a means of extracting energy from the rotor to provide the required vertical force, and none of the helicopters in common use today is suitable for landing gently at zero ground speed in still air from an approach glide of this kind.

As the speed of the approach glide is increased above the minimum airspeed it again becomes possible to commence a pull-out, but a considerable amount of energy is required to complete this manoeuvre and, in the case of the Hoverfly I., a simple pull-out cannot be completed until the speed of the approach glide has risen to somewhere between 45 and 50 m.p.h. I.A.S. Above this speed the collective pitch control can no longer conveniently be used to assist in arresting downward velocity in an actual landing, and for this reason I will refer to the approach speed at which a simple pull-out is just possible, as the change-over speed.

Above the change-over speed a horizontal float becomes possible after the pull-out. The minimum speed at the end of an ordinary float occurs

when the kinetic energy of the forward motion is exhausted and it is basically the same speed as that represented by the length of the thick arrow. There is, however, a difference between conditions in a glide and those in a horizontal float. This is illustrated by the small diagrams in the centre of the illustration, which show that whereas in a glide the Total Air Force is vertical and equal to the weight, in a float it is the lift which is vertical and equal to the weight. Since the disposition of the forces is otherwise identical it follows that they are slightly bigger in a float for the same rotor incidence and the corresponding speed is approximately 10% higher, so that for the Hoverfly I the minimum speed at the end of an ordinary float is about 28 m.p.h.

The lower half of the illustration merely summarizes part of what we have seen in considering the top half. We have already noted that the kinetic energy of forward or linear motion depends on the square of the speed and the lower curve shows how the initial energy of the approach glide increases with speed. It also indicates roughly the energy required for the pull-out and the rapid manner in which the energy available for the float increases with the speed of the approach glide.

Now, in an emergency the collective pitch control is sometimes used at the commencement of an engine-off landing, but our practice of engine-off landings is still almost entirely based on the azimuth stick as the instrument for eliminating downward velocity. Therefore, if we consider only engine-off landings corresponding to engine failure at a sufficient height to allow the pilot full choice of his approach, I think I will not be treading on too many toes if I regard the flare-out as a special kind of pull-out and say that our present practice is based on the motions of pull-out, horizontal float, and final sit-down with the aid of the collective pitch control.

In engine-off landings of the kinds usually practised, the float is sometimes absent, and so occasionally is the use of the collective pitch control. Also the collective pitch control is sometimes used to cushion the fall of the helicopter after a flare-out some distance above the ground and sometimes merely to hold it in the air while it continues to lose forward speed after the end of a normal float. But before we consider these motions in detail I must first clear up a statement which I made earlier and which is repeated in Fig. 12, to the effect that the collective pitch control cannot conveniently be used to assist in arresting downward velocity above the change-over speed.

At first sight this seems to be rather odd, because the collective pitch control is at all times a powerful means of arresting downward velocity and whereas it is the only means of doing this from glides at the minimum airspeed, its effectiveness is also very considerably increased in forward flight. In fact, even if a fully-loaded Hoverfly I. is put into a glide at any A.S.I. reading between, say, 35 and 70 m.p.h., the altimeter hand, which rotates quite fast in a steady glide, can easily be stopped momentarily by pulling up the pitch lever even if the speed is kept constant and the throttle shut. At an A.S.I. reading of between 40 and 60 m.p.h. the altimeter hand can not only be stopped but it can be held stationary for a brief period during which the machine is flying horizontally without power at more or less the original forward speed.

On the other hand, if an attempt is made to eliminate downward velocity by means of the collective pitch control in a landing from an approach glide

ore than the change-over speed, the pilot will find himself in a dilemma, ause the only way in which he can reduce his ground speed is by tilting helicopter backwards. If he starts to do this before using the collective h control the result will be an ordinary pull-out or flare-out. If he s back the azimuth stick at the same time as he uses the pitch lever he find the helicopter doing an excessively hard pull-out, with the result : his last ground speed will be considerably greater than his first and he have to down pitch and quickly think of some other manoeuvre. Finally, he pitch lever is used first from a glide above the change-over speed, velocity of the helicopter cannot be subsequently reduced to less than minimum steady airspeed, so that the forward component of this velocity be appreciably reduced only at the expense of a heavy landing.

We can now examine the kinds of engine-off landing which can be :tised with the helicopters at present in common use and in this connec-

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Fig. 13. Engine-off landing attitude of Hoverfly I.

ı I have in mind particularly the Hoverfly I., which is a very good machine this kind of practice since it gives the pilot manual control over the lective blade pitch, which I believe to be essential, and it is also so arranged t the main rotor can safely be inclined backwards at quite large angles, n when the tail-wheel is touching the ground (Fig. 13 shows this con- ion). The aircraft is already inclined fairly well backwards and the e could be raised a good deal further without endangering the tail rotor. o, at this point, I must remark that because a landing is a manoeuvre ich is by definition conducted close to the ground and is always seen relation to the ground, the effect of the wind speed on its appearance ses such confusion in the arguments which usually follow that it is olutely essential to base our discussion strictly on no-wind conditions.

The upper part of Fig. 14 shows the essential attitudes and motions an engine-off landing from a high speed approach. The speed figures

quoted are subject to considerable variation, but they are in fact typical of one kind of landing which has been extensively practiced at Beaulieu, where, in initial tests and in subsequent training and practice, well over 200, and probably by now nearer 300, of these landing have been made without mishap. I think this landing is ideal for initial training purposes because it is divided into a number of separate and distinct movements in which mistakes are easily noticed for correction in subsequent practice. It is useful for any ordinary forced landing in open country and it can also be modified to suit many special circumstances. In this landing the collective pitch control is used only in the " extra float," and the manoeuvre comprises a fairly fast approach glide, a gentle pull-out, and a horizontal float, so that it is very similar to an aeroplane landing. The feature which distinguishes it from other engine-off landing practised by rotating-wing aircraft is the deliberate inclusion of the horizontal float after the completion of the pull-out.

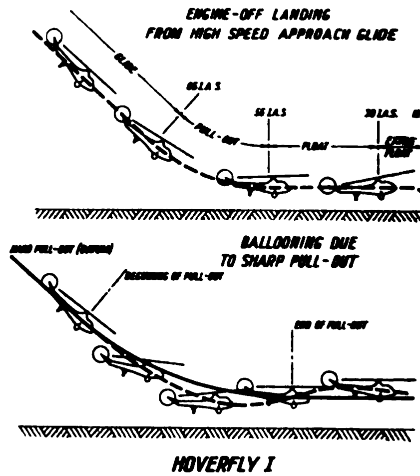


Fig. 14. High speed approach glide.

The float is typically entered at a fairly high forward speed with the fuselage substantially horizontal, and we have already seen the conditions at this point are governed almost entirely by the speed which the pilot chooses for the approach glide. Thus the conditions of entry into the float are voluntary but so long as the float remains level the subsequent deceleration of the aircraft, and the corresponding adjustment of its attitude, are governed exclusively by its aerodynamic characteristics and are therefore involuntary; with the important exception that the pilot can at any time discontinue the float, either by allowing the aircraft to settle onto the ground or by using the collective pitch control to hold it in the air while it continues to decelerate without further alteration in attitude.

The rate at which the rotor incidence, and the attitude of the fuselage, increases during a float, is of particular interest in connection with the landing of helicopters in which a large backward inclination of the fuselage is not permissible near the ground because of the possibility of fouling the tail rotor. The incidence of the rotor varies inversely with the square of the speed, so that the change in rotor incidence for a given reduction in speed is small when the speed is high, but becomes quite large at low speeds. Also the deceleration of the aircraft, as a fraction of G, is simply the inverse

of its Lift/Drag ratio, which is the same as the Gliding Angle The Gliding Angle of the Hoverfly I. varies from about 1 in 4 at 70 m.p.h. down to 1 in 2 at 30 m.p.h., so that if it is brought in fast its initial deceleration is about one-fourth of 1G, which is quite small, but the deceleration will increase to approximately a half of 1G at the end of the float and the speed will then drop off rapidly.

A simple calculation indicates that a float between the speed indicated in Fig. 14 would last little more than 3 seconds, in which time the helicopter would travel about 200 feet, but in a film which I hope to show after the lecture you will see the much longer floats which result from fast approach glides. Owing to the improved Lift/Drag ratio at high speeds the speed lost in the pull-out is less from a fast glide than from a slow one, so that if a Hoverfly I. is brought in at 75 m.p.h. it will still be doing about 70 m.p.h. when it enters the float, which will then last about six seconds and be about 450 feet long.

Six seconds does not sound very long, but you will see from the film that it is much longer than is needed to correct even gross errors in the height of the pull-out. Also during most of this time the rotor incidence changes very slowly so that the pilot has no difficulty in judging when the inclination of the fuselage has gone far enough. For this reason the risk of fouling the tail rotor on the ground during a horizontal float is negligible for a pilot who is at all familiar with the proper approach speed for his aircraft. Even when the speed has fallen as low as 35 m.p.h. at the end of the float the fuselage will still be only slightly inclined backwards, and provided the helicopter has a suitable undercarriage it can quite comfortably either sit down at this speed or use the collective pitch control for an extra float, in which it will continue to slow down without increasing its tail-down attitude. The speed lost in this way depends on the energy stored in the rotors and on the backward inclination of the rotor, but with our present helicopters it would amount to about 15-20 m.p.h.

The extra float can, of course, only be maintained for a brief period because it results from progressive slowing down of the rotor and corresponding increases of collective pitch, neither of which can be continued indefinitely. Nevertheless, the high deceleration at low speeds makes the extra float well worth while and a practiced pilot can regularly use this brief period to knock the forward air speed of a Hoverfly I. down from about 30 m.p.h. to little more than a walking pace, although 12 m.p.h. would be a more usual figure in training.

So long as the approach glide is fast the attitudes and motions of the helicopter remain as shown in the top part of Fig. 14, where the extra float is voluntary and the length of the ordinary float can be varied at will by altering the speed of the approach glide. But when the speed of the approach glide is reduced below about 65 m.p.h., in the case of the Hoverfly I., the character of the landing begins to alter and we find that as the ordinary float disappears the extra float becomes a necessity for correcting errors in the height of the pull-out. Also the rapid changes in fuselage attitude, which before occurred only at the extreme end of the float, now begin to appear at the end of the pull-out and the nature of the pull-out itself begins to be affected to an increasing degree by the inertia characteristics of the rotor, which give rise to a surging or flaring of the rotor speed, so that we

will have to examine this phenomenon before considering the performance of landings from low speed approaches.

Fortunately we can understand the flaring of rotors without becoming involved in lengthy arguments about autorotation, for it is a well-known characteristic of a rotor which is auto-rotating at constant pitch that it has a particular speed of rotation when carrying a particular load and this rotor speed is substantially independent of the forward speed of the aircraft. Also, if the load on the rotor is increased, as in a steep turn, the rotor speed will increase and, similarly, when the extra load is removed the rotor speed will fall again to its original value.

But we have already noticed that, at a given forward speed of the aircraft, there is a particular amount of lift which may be expected from the rotor when it is at a particular angle of incidence under steady conditions. Also, except at very large angles, when the angle of incidence is increased the lift of the rotor will increase, so that if the aircraft happens to be doing a fast glide approach when the pilot increases the rotor incidence the resulting increase in lift will cause the aircraft to start doing a pull-out.

So long as the approach glide is fast and the rotor incidence increased gently the resulting pull-out resembles that of an aeroplane sufficiently closely to require no special comment, but if a sharp pull-out is attempted the picture immediately changes and the lower part of Fig. 14 is an attempt to illustrate what happens.

In a sharp pull-out the incidence of the rotor is rapidly increased to a large value, which would correspond to a high lift in steady conditions. But, if we suppose the rotor incidence to be instantaneously increased, it is obvious that the rotor speed could not increase in a similarly instantaneous manner, although it might grow very rapidly, and the expected large increase in lift does not fully develop until the rotor speed has achieved an appropriately high value. Therefore, at the beginning of a sharp pull-out, the aircraft, in spite of its tail-down attitude, has a tendency to continue its original flight path while the rotor accelerates. This tendency can be seen by comparing the dotted flight path with the continuous line which represents the pull-out which would be done by a helicopter in which the collective pitch control is used to prevent the rotor from accelerating and thus absorbing energy.

When the rotor speed has flared up to something like the value appropriate to the expected increase in lift, the resulting pull-out may be very sharp indeed, but when the downward velocity is eliminated the pilot will immediately want to reduce the rotor incidence in order to enter smoothly into the float. By this time, however, the rotor will have achieved a high rate of rotation and until it has slowed down again it will continue to deliver an excessive thrust, so that in practice it is almost impossible for the pilot to prevent the aircraft from ballooning.

The lower part of Fig. 14 shows the typical motion of a helicopter when a sharp pull-out is done from a high speed approach. (Note : This illustration is over-simplified because the fuselage is drawn parallel to the rotor in each case. For instance in the last figure but one the rotor would be roughly level as shown, but the fuselage would still be in a slightly tail-down attitude, indicating a very forward position of the azimuth stick). In these circumstances the ballooning is of no consequence, because the float gives ample time for the aircraft to settle down. The aircraft can also come

surprisingly close to the ground even when the pull-out is commenced at an apparently reasonable height, but this again is hardly likely to be dangerous because the tail is fairly well up even at the bottom of the pull-out. Nevertheless it is not a pretty manoeuvre at high speed.

So long as the pull-out is gentle the tendency for the rotor to flare is a function of the speed of the approach glide. If the glide is fast the rotor is at a very small incidence so that its thrust is nearly perpendicular to the flight path and very nearly equal to the lift. The small increase in lift required for the pull-out is then produced by correspondingly small increases in the thrust and speed of the rotor. But at low speeds the rotor thrust is inclined backwards at a large angle relative to the flight path so that a small increase in the lift, which is perpendicular to the flight path, can only be produced by a large increase in rotor thrust, which is accompanied by a correspondingly large increase in the speed of the rotor. On the other hand, in a very slow glide near the minimum steady airspeed, the rotor incidence is already so large that to increase it further produces only negligible increases in rotor thrust and speed. Hence there is an intermediate range of approach speeds for which the tendency for the rotor to flare is a maximum.

The upper useful limit of this range occurs slightly above the change-over speed, say 50 m.p.h., for the Hoverfly I. The ordinary float is then negligible and the rotor revs. at the beginning of the extra float, though past their peak, are still high enough for the forward speed to be easily reduced to practically zero. At higher approach speeds the surplus rotor revs. obtained in the flare are damped out before the extra float is commenced.

The pull-out from a glide at the change-over speed should end up with the aircraft at the attitude and speed, say 30 m.p.h., appropriate to the end of a float and with its rotor revs. flared up to their peak value. If a pull-out of this kind is found to be too low it can be tightened with the collective pitch control without altering the attitude of the fuselage, but in general it would be aimed to finish slightly high to allow a reasonable margin for error, so that the extra float which immediately follows would be slanting downwards.

In pull-outs below the change-over speed level flight can be achieved but at much lower forward speed so that practically no energy is supplied to the rotor in the last part of the manoeuvre. A feature of these pull-outs is, therefore, that the peak rotor revs. occur before the end of the pull-out and are largely dissipated by the time it is completed. The classic example of this is the flare-out shown in Fig. 15, in which the motion of the aircraft is, ideally at any rate, completely arrested at the end of the manoeuvre, because the rotor, having achieved its peak revs., continues to develop sufficient excess thrust for height to be maintained while the remaining forward speed is eliminated. During this brief period the rotor is required to produce a large thrust at substantially zero speed so that it decelerates very rapidly. There are a number of interesting considerations relating to the flare-out, but when it is considered as part of the engine-off landing manoeuvre of a helicopter with a tail rotor, the most obvious is that because of the excessive inclination of the fuselage the flare-out must be done well clear of the ground, so that when it is completed the helicopter still has to be lowered vertically onto the ground. As the kinetic energy of the rotor is then largely exhausted it is difficult to do this gently and the practice flare-outs with our present helicopters which I have so far seen have been

done about 15-20 feet above the ground so that the pilots have naturally cheated by using the engine for the touch-down.

There is quite a sizeable family of rotating wing aircraft, typified by the C.30 Autogiro, which do not provide the pilot with control over the collective pitch of the blades, and the proper object of the flare-out is to provide this sort of aircraft with the only means by which motion can be arrested without varying the collective pitch. An aircraft which is properly designed to do flare-out landings is usually of low disc loading and has no tail rotor so that the whole manoeuvre can be performed slowly and close to the ground. In these circumstances the flare-out is a simple and elegant form of landing, although even in the case of the C.30 a forward air speed of 10 m.p.h. is more usual than zero speed at touch-down.

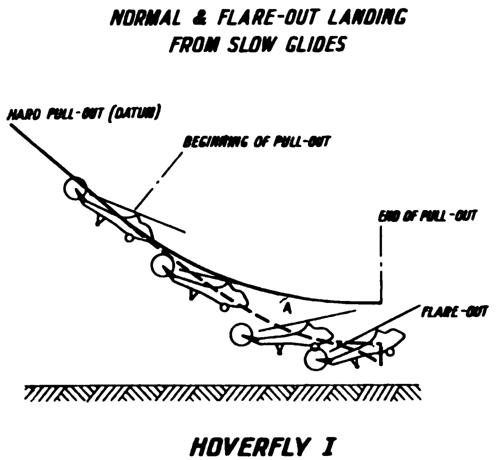


Fig. 15. Slow approach glide.

A feature of a flare-out in which the speed is substantially eliminated without ballooning is that the last part of the manoeuvre is roughly level. In Fig. 15 I think the curvature of the flight path is shown in a reasonably correct manner and it will be noticed that the greatest curvature, and therefore the peak rotor thrust and speed, occurs at the position occupied by the figure A, where the fuselage attitude is still reasonable. Also the position of the point A is not very critical, as far as the rotor revs. are concerned, because, although these fall off rapidly after reaching their peak, they are built up fairly steadily, as indicated by the slowly increasing curvature of the initial part of the pull-out. Therefore, if the fuselage inclination is not allowed to increase beyond the desirable landing attitude, the pull-out will finish at A and the slanting extra float can be commenced immediately while the rotor revs. are at roughly their peak value.

In the Hoverfly I., landings of this kind can be done from glide speeds as low as 40 m.p.h., and if the conditions at the point A are compared with those at the end of a float they will be found to be much the same. So long as the flight path is curved upwards the rotor thrust and revs. will be greater than at the end of a float, but this excess thrust will temporarily remain after the flight path curves downwards and will largely compensate for the remaining downward velocity, which is, in any case, not more than 10 ft./sec., or about 7 m.p.h., even if only half the original downward velocity is eliminated. The forward speed is approximately the same as at the end of an ordinary float and so is the fuselage attitude.

The slanting extra float is therefore much the same as in landings from higher approach speeds. In short, this has the appearance of an easy landing and this was also the opinion of Lt. Hosegood, who did the only one of which I have any direct experience. I have been a passenger in many engine-off landings, including a number, with S/Ldr. Cable, from approach glides at 50 m.p.h. in the Hoverfly I., but this is certainly the easiest I have seen yet as well as the most efficient for setting the helicopter down exactly where it is wanted. I believe this landing is often demonstrated by the Bell 47, also Mr. Hafner's A.R.111 Gyroplane had a collective pitch control and, although I never saw it fly, I think this must be the kind of landing which that remarkable machine was doing before the war.

In future helicopters, the kinetic energy stored in the rotors will be about twice what it is today and an engine-off landing of this kind at zero ground speed will be so simple that I hope it will become the normal landing of a helicopter except in very special circumstances.

We have now completed our examination of the engine-off landings which can be practised with the helicopters now in common use and I turn back to Fig. 12 as a convenient starting point for a discussion of the landings which will be typical of the future. So far we have considered the speed of the approach glide to be varied from 75 m.p.h. I.A.S. down to 40 m.p.h. I.A.S., and in all these landings the use of the collective pitch control has been of secondary importance, being voluntary when the approach glide is fast and assisted by flaring of the rotor when the approach glide is slow.

Landing from fast glides will become increasingly easy with continued improvement in top speeds and gliding angles, but these improvements are likely to be significant while the helicopter is looking for a landing place rather than in the actual landing, because the best gliding performance will always be associated with comparatively low rotor speed. The distinguishing feature of the approach glide of future helicopters will be that the rotor speed will be high by present standards, while the corresponding glide performance remains much the same as it is now. When a landing place is decided on the action of increasing the rotor speed in preparation for the landing will be in some respects analogous to putting down the flaps on an aeroplane. Once this action has been taken the easiest landing is done from a glide at about 30-40 m.p.h., and in future the fast approach glide will be seen only as part of a training exercise designed to separate the motions of a landing for the purpose of initial instruction.

Our present helicopters are already capable of reasonably easy engine-off landings from approach glides as slow as 40 m.p.h., and the problem of future engine-off landings is concerned with the ability of a helicopter to land from steep glides at the minimum steady airspeed. Here the collective pitch control is the only means of effecting a gentle landing and the typical motion of the helicopter during the landing may be described as a pull-up. Also the typical application of the pull-up is for arresting the downward motion of a helicopter which is descending vertically in still air at its terminal velocity.

In these conditions the sinking speed of a C.30 Autogiro would be about 35 ft./secs., of a Hoverfly I., about 40 ft./secs., and of a contemporary design with high rotor speed, about 45 ft./sec., or about 30 m.p.h. vertically downwards, and not so long ago it was quite commonly thought impossible to design a practical helicopter which would be capable of using the kinetic

energy of its rotors to arrest this motion so that a gentle engine-off landing could be made in pure vertical flight.

As you can imagine, my experience with the Focke gave me a rather personal interest in this problem, and, having opened my mouth rather wide on the subject, I thought it might be as well to find some logical basis for supposing that vertical engine-off landings are not only desirable but also possible and even probable. At first this seemed rather a formidable undertaking and I got some quite severe headaches from trying to turn inside-out Dr. BENNETT's well-known calculations on the jump take-off of Autogiros. O'HARA, of Beaulieu, has succeeded in doing this, but fortunately I found that the performance of a helicopter in a pull-up can also be examined in a very simple manner, provided attention is confined to particular cases rather than general solutions, and it was quite easy to show that a gentle engine-off landing in pure vertical flight is possible with a helicopter having characteristics which are within the normal range of current design practice.

So far as I know these first estimates are still the only published information on this subject. They are based on two very conservative assumptions, but all estimates of this kind are to some extent guesswork and it is convenient to examine the more pessimistic guesses first. On the other hand, although I think there is no doubt about the possibility of such landings, the ease with which they can be performed remains a matter of opinion. For this reason I will briefly outline the way in which the estimates were made.

If, for a given helicopter, we know the inertia and profile drag characteristics of the rotor system, and the initial rotor speed and rate of descent, we can find out the rate at which the kinetic energy of the rotor system is being expended at any instant during a pull-up, provided we know the manner in which the rate of descent and the flow through the rotor have varied up till that instant.

The reason why the flow through the rotor is important is easily seen if we consider a helicopter being lowered steadily through the air with its rotor blades outstretched but not revolving. In this case the air will pass freely up through the rotor because there is nothing to stop it. But if the blades are allowed to rotate so that in steady flight they produce a thrust equal to the weight, it is clear that they can only produce this thrust by throwing air downwards or, in other words, by beating down the air which is trying to leak up through the rotor.

While the helicopter is descending it is continuously losing the potential energy, or capacity for doing work, which it possesses by virtue of its height above the ground, and this energy is being lost because it is being expended by the rotor in throwing air downwards (relative to the ground).

Now, if there were no other losses in the system, the potential energy supplied would be equal to the energy required by the rotor to induce the required downward flow of air. Also the downward velocity of this induced flow would be exactly equal to the rate of descent, that is, exactly equal to the speed at which air is trying to leak upwards through the rotor. In consequence, there would be no flow at all through an ideal rotor which is rotating freely in steady vertical descent.

Thus any flow through a descending rotor is a measure of the energy which is being absorbed or given out by the rotor itself as distinct from the potential energy which is being lost by the aircraft as a whole. For instance,

a certain amount of energy is absorbed by a real rotor in overcoming the profile drag of the rotating blades and therefore in steady vertical descent potential energy must be supplied at a greater rate than is needed to produce the required induced flow. Thus the steady rate of descent of a real helicopter is greater than the downward velocity of the induced flow so that air leaks upward through the rotor at a small velocity.

Again, in the particular case of hovering flight without engine power, we know, for instance, that the whole of the downwash through the rotor is created by energy extracted from the rotor. Also for any rotor speed we can calculate the rate at which additional energy is being extracted to overcome the profile drag of the blades. (The information required to do this is obtained from standard curves such as those shown in Fig. 16, which refer to the blades of the Hoverfly I. and of a helicopter of contemporary design).

Therefore, if we know the inertia characteristics of the rotor system, we can find the rate at which it is decelerating at any rotor speed. But we have already seen, in the case of an ordinary float, that when deceleration is known as a function of speed a very simple calculation will tell us how long it takes for the speed to fall from its initial value to the minimum permissible. Thus we can easily calculate how long a helicopter can remain in hovering flight, or any other steady condition, after the engine has failed.

In a very similar way we can estimate the extent to which the rate of descent of a helicopter can be reduced in a pull-up without engine power. The calculation is still very simple, but in a pull-up the rotor thrust, the rate of descent, and the flow through the rotor are all varying, so that before an estimate can be made it is necessary to state the kind of landing which is to be considered. For academic reasons it might be convenient to consider a landing in which the coning angle is constant or one in which the rotor thrust varies in a particular manner with rate of descent. But in a real pull-up the rotor thrust ought to be under the control of the pilot and I think a practical case is fairly well represented by the motion of a helicopter doing a pull-up at constant thrust, which corresponds to applying a constant pressure to the brake pedal of a car. To get a comprehensive picture it is then only necessary to compare the performance of the helicopter in a number of pull-ups at different amounts of constant thrust.

The assumption of constant rotor thrust means that the pull-up is done at constant deceleration and the rate of descent is then known at any instant. Also, if the thrust and rate of descent are known at any instant, we can find the corresponding flow through the rotor from Fig. 17, which, so far as we are concerned, shows the relation between the rate of descent of a helicopter (plotted here as $\frac{1}{f}$) and the flow through the rotor (plotted here as $\frac{1}{F}$) when the thrust is constant. This curve is in three parts, which are labelled to show to what condition of flight they refer. It is not a calculated curve, because there is no reliable means of calculating it. Instead, it is an estimate based on model tests and on a few tests of full scale rotors. The precise shape of the curve remains to be determined and is probably also a function of disc loading. Perhaps the best thing I can say about this particular curve is that, apart from fitting a few test results, it is cribbed

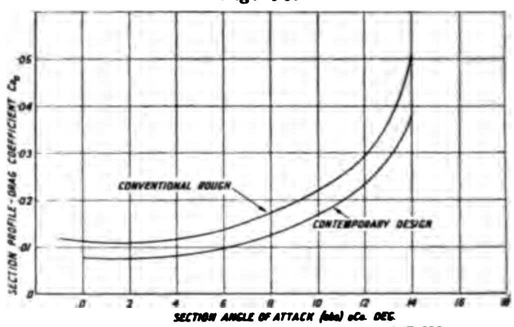
from the best possible authorities, so I don't think it will be suggested that the probable inaccuracies in its shape would seriously affect conclusions with regard to pull-ups.

In steady vertical descent we can calculate the upward flow through the rotor which provides the energy required to overcome the profile drag of the blades, so that we know $\frac{1,}{F}$ which is small, and we find that the operating state of the rotor is then defined by a point near the lower end of the top branch of the curve. From the vertical scale we have the corresponding value of $\frac{1,}{f}$ from which the rate of descent can be calculated. Similarly, if we know the rate of descent we can use the curve to find the corresponding flow through the rotor.

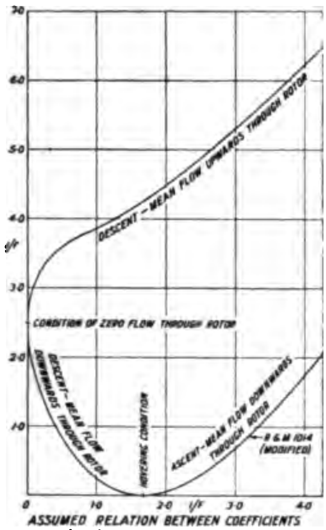
In a pull-up at constant thrust we know the thrust and the rate of descent at any instant, and if we assume that the curve applies to unsteady as well as to steady motions, we can find the corresponding flow through the rotor. If the pull-up is performed at all rapidly this assumption is grossly conservative, as we will see later, but even so the resulting estimates are quite encouraging.

When all the necessary information is collected together it can be fed into a very simple equation which shows the manner in which rotor speed falls off with time after the commencement of a pull-up. The results are shown in Fig. 18 for a typical contemporary design in five pull-ups at

Fig. 16.

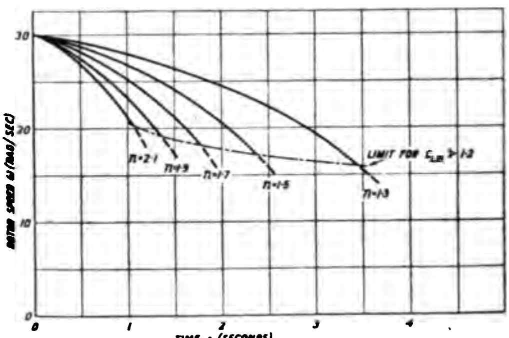


ASSUMED VARIATION OF PROFILE DRAG COEFFICIENT FOR TYPICAL HELICOPTER BLADE AEROFOIL SECTIONS.



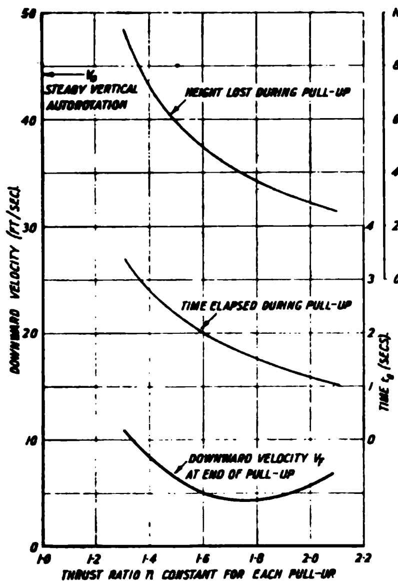
ASSUMED RELATION BETWEEN COEFFICIENTS υ/f & V/F FOR FULL SCALE ROTORS.

Fig. 17.



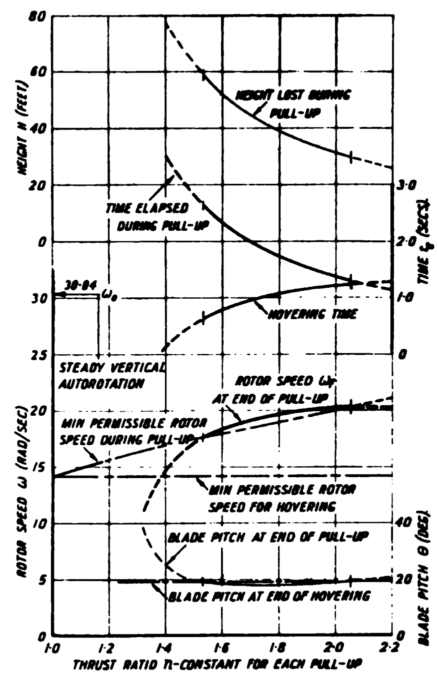
HELICOPTER A. VARIATION OF ROTOR SPEED DURING PULL-UPS.

Fig. 18.



HELICOPTER A. PERFORMANCE IN VERTICAL PULL-UPS WITHOUT ENGINE POWER.

Fig. 19.



HELICOPTER C. PERFORMANCE IN VERTICAL LANDINGS WITHOUT ENGINE POWER.

Fig. 20.

different amounts of constant thrust. The thrust is expressed here as the ratio n, so that the right hand curve refers to a pull-up in which the rotor thrust is 1.3 times the weight, and the left hand curve refers to a pull-up when the thrusr is 2.1 times the weight. The horizontal scale is seconds, but the vertical scale is in radians per second, so that the rotor speed in r.p.m. would be slightly less than ten times the figures shown. The initial tip speed of this rotor is about 705 ft./sec., or 0.64 times the speed of sound.

As the rotor speed falls off while the thrust remains constant the blades would ultimately either stall or cone up until they reached their upper stops. In this design they would stall first, and each curve is continued to a point where the mean lift coefficient of the rotor blades has risen to 1.2, which is taken to indicate stalling and therefore the end of the pull-up. The time spent in the pull-up is therefore known in each case, so that the rate of descent at the end of the pull-up is easily calculated. The way in which the rate of descent at the end of the pull-up varies with the thrust during the pull-up is shown in the lower curve of Fig. 19.

The other curves in this diagram show the way in which the height lost in the pull-up and the time spent in it, very with the rotor thrust. According to this diagram the pull-up can be commenced at any height between 100 ft. and 20 ft. without the final velocity exceeding 12 ft./sec., which is the capacity of a normal undercarriage, while the final velocity

would be less than 6 ft./sec. if the pull-up is commenced between 60 ft. and 30 ft. from the ground.

As an example of pessimism I think you will agree that this is not a bad effort. Nevertheless, the curves do not indicate that the helicopter would stop and as I was reluctant to abandon the conservative basis of these estimates it was necessary to find some means of representing the degree of improvement which could be expected without major alterations in the design. If such an improvement were needed in an actual case it would be obtained by small decreases in disc loading and solidity and by small increases in rotor speed and blade weight, but to preserve a direct comparison in the estimates I lumped these all together and represented them by a single increase of 30% in the weight of the main rotor blades, which amounts to a 2% increase in the total weight of the aircraft. As this particular design can hover in still air at much more than its normal weight, I don't think even this unnecessarily large increase of 2% would noticeably affect the normal performance. The effect on the performance in a vertical pull-up is, however, quite impressive, as shown in Fig. 20.

The thick curve in the middle of the diagram shows the way in which the rotor speed at the end of the pull-up varies with different values of the thrust. The slanting chain-dotted line just below the thick curve indicates the way in which the minimum rotor speed, at which blade stalling occurs, increases when thrust is increased. Comparing this slanting line with the thick curve we find that the rotor speed at the end of the pull-up exceeds the minimum permissible over quite a large range of variations in thrust. Within this range the helicopter will be brought to rest in a pull-up without stalling of the blades and the rotor speed at the end of the pull-up is then still a good deal higher than the minimum which is permissible in hovering flight, so that a brief period of hovering flight will be possible before the helicopter settles onto the ground. The time elapsed during the pull-up and the time available for hovering are indicated by the curves immediately above the thick curve.

Here again the performance is under-estimated because the hovering time refers to hovering in free air and makes no allowance for the ground cushion. Also, a closer inspection of the thick curve shows quite clearly that the assumption of constant thrust does not represent the most effective pull-up because if we consider the right hand end of the thick curve where it crosses the slanting line it is obvious that although the pull-up cannot be continued at the same high thrust it could quite well be continued at a lower thrust, in which case the helicopter would have started to go up again before blade stalling occurred.

In a typical landing in which the pull-up is done at constant thrust, the motion of the pitch lever would be as shown in Fig. 21, where the sharp increase in pitch at the beginning of the pull-up corresponds to the sudden increase of thrust to the value which is afterwards held constant.

(The figures in this diagram are calculated in a rather crude way and are intended to indicate motion of the pitch lever rather than absolute values of blade pitch, which is shown too small by about a degree).

The sudden decrease of pitch at the end of the pull-up would then be necessary to prevent the helicopter from rising again. On the other hand we have already noted that the thrust in a pull-up ought to be high at the

beginning and low at the end, so that in the most effective pull-up the initial sharp increase in pitch would be even more marked than in Fig. 21, while there ought to be a less marked reduction in pitch at the end of the pull-up. In fact, this diagram suggests that the most efficient pull-up is one in which the pitch is suddenly increased by about 10 degrees and then left alone until it is wanted for final adjustments as the helicopter settles onto the ground. This action of the pitch lever could, of course, be obtained automatically by pressing a button, but I do not think automatic devices of that kind should be encouraged in piloted aircraft.

Now, if the pull-up has been performed in the most effective manner the original helicopter could have stopped quite easily without the blade weight being increased at all, and at this point I was prepared to let the matter rest for the time being because it was already clear that engine-off

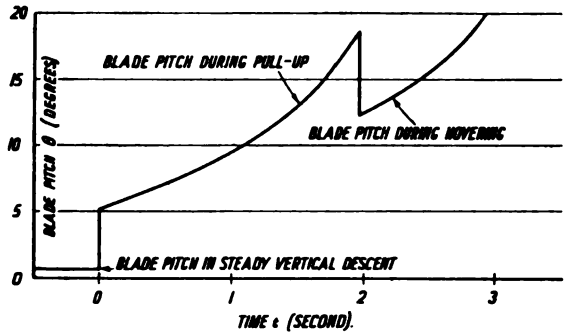


Fig. 21.

HELICOPTER C. MOTION OF PITCH CONTROL IN A VERTICAL LANDING WHEN $n = 1{\cdot}7$ IN PULL-UP.

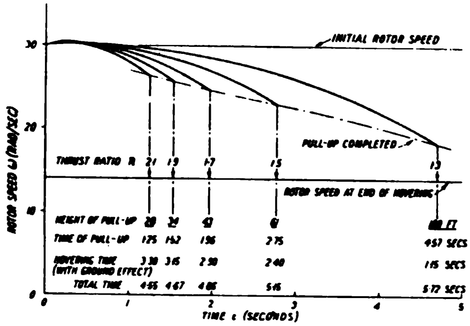
landings in pure vertical flight are possible within the range of our current design practice. But I did mention that not only had the ground effect been neglected in hovering, but also the inertia of the air had been neglected during the pull-up, and this latter feature of the estimates had since been the subject of quite severe criticism on the grounds that they are too pessimistic.

Now the assumption of constant rotor thrust during the pull-up implies that at the beginning of the pull-up the thrust is instantaneously increased to n times the weight of the aircraft and the reason why these estimates are pessimistic is that to use the curve of Fig. 17 in the way it was used is equivalent to saying that the velocity of the downward induced flow is also increased instantaneously to n times its normal value. But the induced flow is not something which happens only in the plane of the rotor—on the contrary, to speed it up entails altering the whole flow pattern around the rotor and the inertia of the air involved in this flow pattern is considerable, so that an appreciable time is required to establish a change in the induced velocity.

I do not know of any reliable method of estimating this time, but certainly in a pull-up the induced velocity would not increase to the value appropriate to the vortex ring state through which the helicopter is assumed to pass in the estimates we have considered. Also, if the pull-up is quick, it would in practice be performed close to the ground, which would further

interfere with the build-up of induced velocity and in these circumstances I think it is not unreasonable to suppose that the increase in induced velocity is small.

If this is so, the effect on the performance of the pull-up is very considerable, as shown in Fig. 22, which illustrates the performance of the original helicopter with light blades, assuming the induced velocity remains throughout the pull-up at the value appropriate to steady vertical descent. Now this diagram and the previous estimate for this helicopter represent two extreme possibilities and the truth lies somewhere between them. For instance, an unaltered induced velocity cannot reasonably be accepted in the case of the right hand curve, which represents a pull-up started at 100 ft. and lasting over 4½ seconds, and in this case the previous estimate of a final velocity of 12 ft./sec. is probably somewhat nearer the truth. On the other hand it is very unlikely that anyone would start a pull-up at 100 ft., and when we consider the more usual height of 40-50 ft. it is clear that the pull-up would be over in approximately two seconds and would take place largely within the ground cushion. In these circumstances there will probably not be any large build-up of the induced flow and I believe the figures quoted in this diagram are close to the truth for typical pull-ups at constant thrust in actual future landings.



HELICOPTER A. INDUCED VELOCITY UNALTERED BY PULL-UP.

Fig. 22.

But we have already noticed that the rotor thrust should be high at the beginning of a pull-up and low at the end for maximum effectiveness and this is very clearly indicated in Fig. 22, which shows that in the first half-second of a pull-up the pilot has at his command a brake of almost unlimited power, within the range which he is likely to require, which costs practically nothing in rotor energy. The slight flaring of the rotor when the pitch is increased is a phenomenon which must occur whenever the thrust of an auto-rotating rotor is suddenly increased without a correspondingly sudden increase in the induced flow. The phenomenon is very short-lived in vertical flight because it can only occur while air is flowing upward through the rotor, whereas the extra thrust very quickly reduces the rate of descent to less than the velocity of the induced flow, after which the flow through the rotor is downward. In practice the phenomenon would not produce any significant increase in rotor speed, but it would be noticeable as a small time-lag between the extra thrust and the falling-off of rotor speed.

When allowance is made for the inertia of the induced flow the corresponding estimate of the motion of the pitch lever during the landing will also be altered and the initial sharp increase in pitch shown in a previous

diagram would correspond to a much larger increase in thrust so that the collective pitch control may be expected to be more sensitive and more powerful than was originally estimated.

The speeds and decelerations shown in this diagram for a typical pull-up from, say 50 ft., are practically the same as in the extra float at the end of an ordinary engine-off landing, namely, an initial speed of 30 m.p.h. and a mean deceleration of slightly more than half of 1G. Considering the extra braking power which is available if required, and the allowance of, say, 2 seconds of hovering time for correction of mistakes, it does not appear that a landing of this kind would be very difficult, unless it can be shown that judgment of height and speed in vertical flight is fundamentally different from that in horizontal motion. Personally I don't think there will be any difficulty of this kind and I believe that if a pilot approaches the vertical landing gradually in the course of his training he will find it comparatively easy.

The vertical landing is certain to be an important feature of a pilot's training because it is typical of all landings from glides at the minimum airspeed. In the event of engine failure over built-up areas, or over wooded or uneven ground, a glide at the minimum airspeed is attractive because it allows the pilot to steepen his glide path immediately he sees a clear space for landing, without waiting for the completion of the pull-up which would intervene at higher speeds. Also, when descending steeply, he has complete freedom to use the azimuth stick in changing his flight direction without incurring changes in the flight path speed which would upset his judgment. Where the helicopter must be accurately positioned for a pull-up in a confined space this freedom and directness in the approach will be valuable features of a helicopter which is capable of vertical engine-off landing.

The normal engine-off landing of such a helicopter would naturally be done in the easiest circumstances and these will correspond to a glide speed of 30 to 40 m.p.h., where the landing will include a little pull-out, a little flare-out, and plenty of pull-up, all combined in a manoeuvre which will be so easy and will take such a long time anyway that the power of the engine could not very well be used even if it was still available. When we have got to this stage we will be able to return to the practice of the pre-war flying clubs, where we were taught that every landing should be done as though it were a forced landing in normally easy circumstances. I think this is a very wise teaching and I hope that in the course of the next few years the use of engine power will largely disappear from the normal landing of a helicopter.

WESTLAND-SIKORSKY S-51.

To conclude my talk I have brought with me some slides illustrating the activities of the Westland Co's. S-51 helicopter in the demonstrations which it has been giving this summer in all parts of the country. The S-51 is a magnificent aircraft with a long history behind it and a great future in front of it. As you know, our job at Westlands is to produce a British version and we have made good progress with the work of translating the present American aircraft into British materials, with the Alvis Leonides

Fig. 23. Westland's S-51 lifting a Bailey bridge panel.

Crown copyright reserved.

as an alternative to the Wasp Junior engine. The extensive detail revision of the American drawings to meet British design requirements and to accommodate British proprietary parts, and the considerable work entailed in preparing for production, are being pushed ahead at Westlands with all possible speed by a growing team of able and enthusiastic engineers, with every intention of consolidating the great advantage which we have from our close connection with the Sikorsky Division of United Aircraft.

The slides show typical items from demonstrations :—

1. Use of Air/Sea rescue hoist.
2. Parking between cars.
3. Taking man from buoy.
4. One item of our normal demonstration included lifting a dummy girder, and this apparently tickled the fancy of Sir Donald Bailey, of Bailey Bridge fame, who invited us to give a demonstration at the Military Engineering Experimental Establishment at Christchurch. For this occasion we fitted the machine with a special weight-lifting beam and here you see it lifting :—
   (i) A section of a Bailey Bridge weighing 600 lbs. (Fig. 23).
   (ii) An engine and mounting weighing 960 lb.
   (iii) At another demonstration we arrived with the special beam in place and, on looking round for something to lift, we found a crate containing a Gipsy Six engine, which is being lowered on to a very small trolley.

These illustrations show the aircraft operating in practically still air without any benefit from the ground cushion, and you will remember from Mr. SIKORSKY's lecture that the weights mentioned are far less than the

eighteen people which can be lifted in a normal take-off or with the help of a little wind. Nevertheless they represent a very useful practical performance, for instance, in carrying food to isolated places.

5. In the course of our demonstrations we gained valuable experience in operating in and out of the major London Airports and in flights over the Metropolitan area. These flights included many landings at Barnes, and others in Regents Park, on the Horse Guards Parade, etc. Here you see the S-51 after landing on the roof of a strong room in the bombed area behind the B.B.C. and immediately outside this lecture hall.

Owing to a fit of absent-mindedness on my part my final Slide is missing. It was an attractive photograph showing two S-51's leaving Yeovil for our original demonstration at Barnes, but anyway that is a sight which I hope will shortly be a commonplace at helicopter airports all over the country. In the meantime much remains to be done and it would be foolish to indulge in unnecessary prophecy, but we hope that by this time next year Westland-Sikorsky S-51's will already be in commercial operation.

In conclusion I take this opportunity of thanking the Ministry of Supply for permission to use the material for the first part of this talk and particularly for the assistance I have received from RDL2 and the A.F.E.E. Similarly I am indebted to the Westland Company for permission to discuss the S-51 and for their assistance in the preparation of notes and slides.

Finally I would like to say that I very much appreciate the privilege and pleasure of this opportunity to address the Helicopter Association and I thank you very sincerely for your kind attention.

NOTE—Illustration of the full range of slides shewn has not been possible owing to lack of space—ED.

FILM SHOWN ILLUSTRATING MR. FITZWILLIAM'S LECTURE.

This film was taken at Beaulieu in the summer of 1945 and it shows seven engine-off landings by a Hoverfly I. from approach glides at a speed of rather more than 75 m.p.h. A.S.I. It is interesting because it not only shows the long float which results from a high speed approach but also the pull-outs in the first three landings were done very sharply owing to a misunderstanding between the pilot, Lt. HOSEGOOD, and myself.

These landings followed the original experiments which were flown by S/Ldr. CABLE, and they were part of a series in which the length of the extra float was varied from zero to the maximum by varying the amount of collective pitch used. The extra float could have been a good deal more effective than it was in these tests because you will notice that the tail-down attitude of the aircraft could quite safely have been considerably increased. Also in a real forced landing the engine would be dead and the pitch control could be used to its full extent. In these landings, although the engine is not used, it is still idling, and the pitch and throttle synchronising gear of the Hoverfly I. is rather awkwardly arranged so that even when the twist-grip throttle is shut as far as possible the engine cannot be prevented from interfering with the landing if the pitch is increased beyond about 10°.

(Note.—Several members seem to have deduced, from the stroboscopic effects in the film, that the engine was employed in these landings. This is definitely not the case, as could be demonstrated by reference to the increasing coning angle in the " extra float "). In these landings the air speed at touch-down is about 12 m.p.h. or less, but you will notice a peculiarity of the Hoverfly I. which results in the forward speed increasing on the ground if the rotor is allowed to tilt forward after landing. Because of this the aircraft will continue to run along the ground for a surprising distance unless the azimuth stick is held hard back.

This motion can, of course, be arrested immediately by use of the brakes, and you will notice that we fitted small bumper wheels on either side to guard against the nose being rubbed on the ground. With these in place the aircraft was landed on the runway at speeds up to 25 m.p.h. and on grass at about 12 m.p.h., but in spite of the rearward position of the main wheels, and the fact that the bumper wheels projected noticeably below the nose, they only contacted the ground twice and on both occasions this was because the main wheel brakes had been left hard on by mistake.

MR. PULLIN'S VOTE OF THANKS TO MR. FITZWILLIAMS.

LADIES AND GENTLEMEN,—It gives me great pleasure to propose a hearty vote of thanks for the excellent lecture so well prepared and delivered by Mr. Fitzwilliams.

Mr. Fitzwilliams commenced his career in rotating wing aircraft when he was transferred from the Turbine Department of Messrs. G. & J. Weir, Ltd., to the Aircraft Section in 1939, which was under my supervision. He was so determined to get into the rotating wing field that he really organised own transfer and judging by the progress he has made in the art it will be appreciated that you cannot keep a good man down. This is especially true with Mr. Fitzwilliams, and he also takes part in the airborne experiments.

As I understand the time at our disposal this afternoon has practically expired, I should like you to join me now in a very hearty vote of thanks to Mr. Fitzwilliams for the excellent lecture we have so much enjoyed.

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Editorial.

In this, the third issue of the *Journal*, the Council think it appropriate to give a brief resume of the work which they have undertaken on behalf of the Association in the general interests of furthering the development and use of the helicopter. It must, however, be realised that much work has yet to be done if the helicopter is to take up its proper role in the field of transportation, and if its many advantages are to be employed to the fullest extent.

The Ministry of Civil Aviation has formed various working Groups for the framing of suitable regulations covering the issue of Pilot Licences and the Regulatory Aspects of helicopter operation, also, the Ministry of Supply has arranged meetings to consider the requirements for Blind Flying. Our Association, now being accepted in official quarters as the authoritative voice in these matters, has, on these occasions been invited to express its views, and many of our members have attended the above-mentioned meetings on behalf of the Association.

Other matters at present under discussion with the authorities affect the Licensing of Engineering personnel ; the planning and location of suitable landing places and the adaptation of existing legislation to allow the helicopter the freedom it requires, and other allied subjects, all of which have an important bearing on the future of rotary-wing aviation.

The Council is glad to report to members on the excellent co-operation exhibited by all the Government Departments concerned. This work continues and from time to time calls will be made upon members to volunteer for duties on various Sub-Committees which it is being found necessary to form in order to ensure that the Association's interests may be represented.

Trinity House Helicopter Trials

It has already been reported in the last *Journal* that Helicopter Lighthouse rescue and relief trials were carried out last October, when a Westland-Sikorsky S-51 carried our Vice-Chairman MR. NORMAN HILL, from the windswept gallery of the Dungeness Lighthouse to a lifeboat, in a successful endeavour to prove the suitability of the Helicopter for this type of rescue and relief work.

We now hear that during February of this year, the Elder Brethren of Trinity House had occasion to make a genuine emergency call for a helicopter relief. The crew of three men on the Wolf Rock Lighthouse, eight miles off Lands End, were overdue for relief owing to the bad weather and to the fact that their rations were almost exhausted, the Trinity House Tender, the 300-ton *Triton*, having made numerous unsuccessful attempts to bring relief to the Lighthouse.

As on the occasion of the earlier trials, the Westland Aircraft Company collaborated with the British Electric Traction Company, and on the morning of February 7th, despite high winds gusting up to 45 knots and a ten-tenths cloud base at 800 feet, MR. A. E. BRISTOW, the Pilot, and MR. L. SWAIN, Engineer, took off from the Royal Naval Air Station, Culdrose, in the Westland-Sikorsky S-51. The flight to the Lighthouse was made at 100 feet, and on arrival the machine hovered while 250 lbs. of provisions were lowered by the hydraulically-operated winch to the crew of the Lighthouse.

These trials and their results are significant in showing that the helicopter is now generally recognised as a practical and useful vehicle, and due credit should be given to the Companies concerned for their initiative, the results of which will undoubtedly reflect beneficially throughout the British helicopter industry.

SIXTH LECTURE

Helicopter Rotors

By A. McCLEMENTS, A.M.I.MECH.E.
A.R.T.S. (GLASGOW)

A lecture presented to the Helicopter Association of Great Britain, on Saturday, 20th September, 1947, at Manson House, 26 Portland Place, London, W.1.

H. A. MARSH, A.F.C., A.F.R.Ae.S., IN THE CHAIR

INTRODUCTION BY THE CHAIRMAN.

Ladies and Gentlemen,

It is with pleasure that I introduce to you today MR. MCCLEMENTS, who is going to talk to us on the subject of " Helicopter Rotors."

MR. MCCLEMENTS is a relatively newcomer to the rotary wing industry and only claims a modest two years or so of direct connection, first with the Ministry of Supply and now as experimental engineer to the Helicopter Development Unit of British European Airways Corporation. Apart from this, it is quite obvious that he has given a great deal of thought and work to the subject of his lecture.

Speaking from personal experience, I can assure you that he was invaluable to all those in the industry during his time at the Ministry of Supply and will, I am sure, be equally so in his present appointment.

On behalf of the Association, may I welcome our guests and trust you will be well rewarded for coming along.

MR. A. MCCLEMENTS.

INTRODUCTION.

In this paper certain mathematical relationships are derived which it is thought will be helpful in the detailed consideration of rotor designs and during study of the influence of the rotor on the aircraft as a whole.

In general, the contents of the paper are straightforward insofar as they are statements of fact. However, this is not so right throughout the work because some of the assumptions made are based on incomplete data and are therefore likely to lead to controversy. In making such assumptions this possibility is appreciated, but, rather than omit them, they are included in the belief that the resulting discussion will be of general interest.

In considering the factors which influence the effect of the blade on the aircraft as a whole it soon becomes apparent that their number of possible combinations can lead to complexity unless simplifications are resorted to. In order, then, to derive expressions which are both manageable and useful, the treatment here adopted is limited where necessary to extreme cases within which operational conditions are thought likely to prevail.

A complete study of this subject would take account of the power parameter throughout. This is not done in the present work and the omission should be noted at the outset for the purpose of appreciating the limitations of some of the expressions derived.

In order to explore general trends it has been necessary to assume values for certain constants and for such parameters as disc loading and tip speed. The values so used for the constants are based on current design experience and the tip speed and disc loading adopted are chosen as representative of a conventional medium speed machine.

2. SUMMARY.

(The paper is in 2 parts).

In PART 1 basic relationships of a general nature are derived between such variables as blade weight, centrifugal force, moment of inertia, aerodynamic lift, coning angle, and such dimensions as the radial positions of the blade centre of gravity, centre of percussion, radius of gyration and centre of resultant lift. These basic relationships are used to derive the general equation of blade equilibrium. The general equation of blade equilibrium, used in conjunction with the basic relationships, enables expressions to be determined which define the following within the limits of the assumptions stated in para. 4.

(*a*) Coning angle for maximum axial rotor lift on the assumption that the blade has no acceleration in the flapping plane about the flapping hinge.
Note.—Consideration of power requirements would show that this angle would never be used as a steady design condition ; it is, however, of academic interest.

(*b*) Blade weight/Aircraft weight ratio. This ratio is determined in terms of rotor angular velocity, rotor radius and coning angle.
Note.—While it is shown that increase in coning angle results in a depreciation of this ratio, it does not follow that it is a good thing from the weight viewpoint to adopt lırge hovering coning angles. Large coning angles necessitate an increase in rotor power for the same all-up-weight and the power parameter must be introduced to get an overall appreciation of the effect of coning angle on payload. This is done in (*c*) under.

(*c*) Best hovering coning angle from viewpoint of weight economy for any given engine power.

(*d*) Loss in useful load when a coning angle other than the best from the weight viewpoint is adopted.

(*e*) Change in coning angle with change in blade lift.

(*f*) Aircraft acceleration in the direction of the rotor axis of rotation and maximum angle of blade flap during acceleration.
Note.—It should be understood that accelerations arising from increases in blade lift coefficient of appreciable magnitude are likely to be of short duration and made possible by the necessary power increase being supplied from the rotor kinetic energy. Such accelerations, while unlikely to be maintained, are important from the stressing viewpoint.

(*g*) Time taken for the blade to move from one coning angle to another when the blade lift coefficient is suddenly changed.

In Part 2 the aircraft is broken down into various components and the ratio of the weight of each of these components to the all-up-weight is studied in relation to the rotor radius. On the basis of the assumed manner in which the aircraft component parts vary with the rotor size, and, in particular, that :—

(i) the ratio of part of the transmission weight to the all-up-weight varies as the square of the rotor radius ; and
(ii) the disc loading and tip speed do not vary as the rotor radius is changed ;

expressions are derived from which the following quantities can be studied :—

(*a*) rotor size for maximum useful load lifted ; and
(*b*) rotor size for maximum useful load/all-up-weight ratio.

PART 2 of this paper is meant to apply only to machines having conventional engines, since the expressions derived are not necessarily applicable to jet driven rotors with simplified transmission systems.

3. LIST OF SYMBOLS.

Blade radial length	R_{Ft}
Blade weight per unit length at radius R ..	w Lbs/Ft.
Total blade weight	Wb Lbs.
Moment of blade weight about flapping hinge ..	MWb Lbs. Ft.
Resultant blade centrifugal force	C_F Lbs.
Moment of resultant blade centrifugal force about flapping hinge	Mc_F Lbs. Ft.
Aerodynamic lift per unit length of blade at radius R	1 Lbs/Ft.
Resultant aerodynamic lift on blade	L Lbs.
Resultant aerodynamic lift during hovering ..	L_H Lbs.
Maximum resultant aerodynamic lift on blade ..	L_M Lbs.
Moment of aerodynamic lift about flapping hinge	M_L Lbs. Ft.
Axial component of resultant blade lift	L cos β_0Lbs.
Coning angle of blade	β_0 RADIANS.
Coning angle of blade for maximum axial lift component, when the blade has no flapping acceleration	β_{M_1} RADIANS.

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Coning angle fixed by maximum lift coefficient ..	β_M RADIANS.
Coning angle of blade during hovering	β_H RADIANS.
Hovering coning angle for maximum useful load	β_{H_1} RADIANS.
Maximum angle of blade flap resulting from blade acceleration about flapping hinge	β_F RADIANS.
Blade flapping velocity	$\dot{\beta}_0$ RADS/SEC.
Blade flapping acceleration..	$\ddot{\beta}_0$ RADS/SEC^2
Blade lift coefficient	C_L
Maximum blade lift coefficient	C_{L_M}
Blade lift coefficient during hovering	C_{L_H}
Angular velocity of rotor about axis of rotation ..	ω RADS/SEC.
Blade tip speed	$\cos\beta_0 x\ \omega R$ FT/SEC.
Vertical acceleration of aircraft when $\ddot{\beta}_0$ is zero ..	$N\beta_0$ g FT/SEC^2
Vertical acceleration of aircraft (general case) ..	N g FT/SEC^2
Maximum vertical acceleration which aircraft can experience when $\ddot{\beta}_0$ is zero	N_{β_0} (max.) FT/SEC^2
Radial position of blade centre of gravity ..	k_1 R FT.
Radial position of resultant centrifugal force on blade (*i.e.*, centre of percussion)	k_2 R FT.
Position of resultant aerodynamic lift on blade ..	k_3 R FT.
Moment of inertia of blade about flapping hinge	I Lb. FT. SEC^2
Radius of gyration of blade about flapping hinge	k R FT.
Ratio $\frac{\text{Axial lift component,}}{\text{Blade weight}}$ when $\ddot{\beta}_0 = 0$ ..	$\mathcal{E}\beta_0$
Ratio $\frac{\text{Axial lift component}}{\text{Blade weight}}$ (general case) ..	$\mathcal{E}$
Rotational energy of blade about flapping hinge when vel. is $\dot{\beta}_0$	KE FT. Lbs.
Time taken for blade to cone from one angle to another	t SECS
Revolutions made by rotor in time t	n REVS.
Aircraft all-up-weight	W Lbs.
Weight of transmission parts dependent on rotor torque	WT_1 Lbs.
Weight of transmission parts independent of rotor torque	WT_2 Lbs.

Weight of engine and power plant	W_E Lbs.
Weight of airframe, undercarriage, furnishings, etc.	W_F Lbs.
Weight of tail rotor blades	Wb_T Lbs.
Weight of crew	Wc Lbs.
Useful load	Wu Lbs.
Maximum useful load	W_u (max.) Lbs.
Aircraft all-up-weight minus blade weight ..	W_A Lbs.
Maximum value of W_A	$W_{A\,(max.)}$ Lbs.
Ratio $\frac{\text{Wu (max.)}}{\text{WA (max.)}}$	×
Disc loading	DL Lbs./FT^2
No. of blades per rotor	Z

PART 1.

4. ASSUMPTIONS.

(*a*). The blade flapping hinge is on the axis of rotation. While rotors frequently have off-set flapping hinges the amount of off-set is usually small and unlikely to have any significance in the formulae derived.

(*b*). The blade lift acts normal to the blade surface ; thus the effect of radial air flow is ignored. Since the effect of any radial flow on the direction of the resultant lift vector can only be of secondary importance it is felt that this assumption is justified.

(*c*). If the power input to the rotor is constant and the rotor angular speed is constant, the length of the resultant blade lift vector is constant for all coning angles from zero up to those in which we are likely to be interested. This assumption is unlikely to hold over a large range of coning angles, but it is probably accurate to a close order of approximation for coning angles from zero up to at least 15°.

(*d*). The aircraft has air speed only in the vertical direction.

(*e*). Bending in the blade is ignored. Blade deflection will reflect on the values of the aircraft momentary accelerations derived but are unlikely to seriously influence the limiting values.

(*f*). Air damping on the blade in the flapping plane is ignored. The effect of this assumption will be to under-estimate the time taken for the blade to move from one coning angle to another, but the assumption is unlikely to influence the order of the result which is of interest as distinct from its absolute value.

(*g*). In investigating general trends the values of the blade constants are assumed to be :—

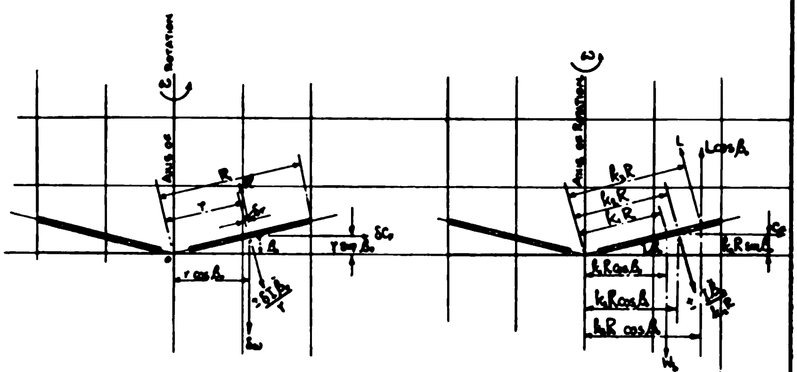
$k_1 = 0{\cdot}42$ where k_1R is the radial position of the blade C.G.

$k_2 = 0{\cdot}56$ where k_2R is the radial position of the blade centre of percussion.

$k_3 = 0{\cdot}72$ where k_3R is the radial position of the resultant blade lift.

The value of these constants will vary from one design of blade to another but probably not greatly since blades are similar insofar as they are long and narrow and of like mass distribution. The chosen values are based on current design experience.

(*h*). Momentary loads on the blades resulting in movements in excess of the hovering coning angle are assumed to cause no loss in blade rotational speed. This is an extreme case which is probably approached in practice because of the high rotational inertia of the rotor maintaining angular speed constant during short periods of excess blade flapping displacement.



FORCES ACTING ON BLADE ELEMENT OF LENGTH δr

FIG. 1

RESULTANT FORCES ACTING ON BLADE

FIG. 2

5. BASIC RELATIONSHIPS.

The following basic relationships used throughout the paper are derived from figure 1 and are applicable to any blade.

(i) Blade weight. $W_b = \int_0^R w \, dr.$

(ii) Moment of blade weight about flapping hinge. $M_{W_b} = \cos \beta_0 \int_0^R wr \, dr$

(iii) Blade centrifugal force. $C_F = \dfrac{\omega^2 \cos \beta_0}{g} \int_0^R wr \, dr$

$$= \frac{\omega^2 M_{W_b}}{g}$$

(iv) Moment of blade centrifugal force about flapping hinge. $M_{C_F} = \dfrac{\omega^2 \cos \beta_0 \sin \beta_0}{g} \int_0^R wr^2 \, dr$

(v) Moment of inertia of blade about flapping hinge.

$$I = \frac{1}{g} \int_{o}^{R} wr^2 \, dr$$

$$= \frac{M_{C_F}}{\omega^2 \cos \beta_o \sin \beta_o}$$

(vi) Lift on blade.

$$L \propto C_L \, \omega^2 \cos {}^2\beta_o \int_{o}^{R} r^2 \, dr$$

(vii) Moment of blade lift about flapping hinge.

$$M_L \propto C_L \, \omega^2 \cos {}^2\beta_o \int_{o}^{R} r^3 \, dr$$

The resultant forces mentioned above are shown acting on the blade in Fig. 2. From Fig. 2 it follows that—

(viii) $M_{W_b} = Wb \; k_1 \; R \cos \beta_o$

(ix) $M_{C_F} = C_F \; k_2 \; R \sin \beta_o$

(x) $M_L = L \; k_3 \; R$

(xi) $I\ddot{\beta}_o = \frac{Wb}{g} k^2R^2 \ddot{\beta}_o$

Now $\frac{Wb}{g} k^2R^2 = \frac{1}{g} \int_{o}^{R} wdr \; k^2R^2$ . . . . . . from (i)

$$= \frac{1}{g} \int_{o}^{R} wr^2 \, dr \text{ . . . . . . from (v)}$$

$$\text{i.e. } k^2 = \frac{\int_{o}^{R} wr^2 \, dr}{R2 \int_{o}^{R} wdr} \quad \text{. . . . . . (a)}$$

Also, $M_{W_b} = \cos \beta_o \int_{o}^{R} wr \, dr$ . . . . . . from (ii)

$$= \cos \beta_o \int_{o}^{R} wdr \; k_1 \; R \text{ . . . . . . from (i) \& (viii)}$$

$$\text{i.e. } k_1 = \frac{\int_{o}^{R} wr \, dr}{R \int_{o}^{R} wdr}$$

$$\text{Again, } M_{C_F} = \frac{\omega^2 \cos\beta_o \sin\beta_o}{g} \int_o^R wr^2\, dr \;.\;.\;.\;.\;.\; \text{from (iv)}$$

$$= \frac{\omega^2 \cos\beta_o \sin\beta_o}{g} \int_o^R wr\, dr\, k_2 R \;.\;.\;.\;.\;.\; \text{from (iii) \& (ix)}$$

$$\therefore\ k_2 = \frac{\int_o^R wr^2\, dr}{R \int_o^R wr\, dr} \;.\;.\;.\;.\;.\;.\; \text{(b)}$$

$$\text{Hence, } k_1 \times k_2 = \frac{\int_o^R wr^2\, dr}{R^2 \int_o^R w\, dr} = k^2 \;.\;.\;.\;.\;.\;.\; \text{from (a)}$$

$$\text{Hence, } I\ddot{\beta}_o = \frac{Wb}{g} k_1\, k_2\, R^2\, \ddot{\beta}_o$$

$$= \frac{MW_b\;\; k_2\; R\, \ddot{\beta}_o}{g \cos \beta\dot{o}} \;.\;.\;.\;.\;.\;.\; \text{(c)}$$

(xii) If position of resultant inertia force on blade $= k_4$ R,

$$\text{then } \frac{k_4 R}{g} \int_o^R wr\, dr\, \ddot{\beta}_o = \frac{1}{g} \int_o^R wr^2\, dr\, \ddot{\beta}_o \;.\;.\;.\;.\;.\;.\; \text{from (ii) \& (v)}$$

$$\text{i.e. } k_4 = \frac{\int_o^R wr^2\, dr}{R \int_o^R wr\, dr} = k_2 \;.\;.\;.\;.\;.\;.\; \text{from (b)}$$

Hence, the resultant centrifugal and inertia forces act through the same point, *i.e.*, at a radius equal to k_2 R which is the blade centre of percussion.

6. FUNDAMENTAL EQUATION DEFINING EQUILIBRIUM OF BLADE ABOUT FLAPPING HINGE.

This relationship is obtained by considering the equilibrium of the blade about its flapping hinge. The couples acting on the blade in the flapping plane are added algebraically and equated to zero. The directions of all the couples are constant except the inertia couple which acts in opposition to the lift couple while the blade is being accelerated upwards and with the lift couple when the upward motion of the blade is being retarded.

The inertia couple is taken as —ve and +ve respectively when it acts with and against the lift couple. Taking moments about the flapping hinge, it follows that :—

$$M_L - M_{W_b} - M_{C_F} - I\ddot{\beta}_0 = 0.$$

From basic relations (iii) and C

$$M_L - M_{W_b} - \frac{\omega^2}{g} M_{W_b} k_2 R \sin \beta_0 - \frac{M_{W_b} k_2 R \ddot{\beta}_0}{g \cos \beta_0} = 0$$

i.e., from basic relations (viii) and (x)

$$\frac{L}{W_b} = \frac{k_1 \cos \beta_0 \left[1 + \frac{k_2 (\omega R)^2 \sin \beta_0}{gR} + \frac{k_2 R \ddot{\beta}_0}{g \cos \beta_0} \right]}{k_3} \quad \ldots\ldots \text{1A}$$

The axial component of lift $= L \cos \beta_0$.

Let $\mathcal{E} = \dfrac{\text{Axial Component of lift,}}{\text{Blade Weight}}$

so it follows that

$$\mathcal{E} = \frac{L \cos \beta_0}{W_b} = \frac{k_1 \cos^2 \beta_0 \left[1 + \frac{k_2 \sin \beta_0 (\omega R)^2}{gR} + \frac{k_2 R \ddot{\beta}_0}{g \cos \beta_0} \right]}{k_3} \quad \ldots 1$$

It will be observed from equation 1 that the axial component of lift from a particular rotor running at constant ωR can be defined alone by constants, coning angle and blade acceleration in the flapping plane. Since blade acceleration is a transient condition the ratio $\mathcal{E}$ may be considered within the limits of two conditions, viz. :—

(*a*) with respect to β_0 alone

and (*b*) with respect to $\ddot{\beta}_0$ and β_0.

Consideration of (*a*) will lead, among other things, to the choice of coning angle which will result in maximum useful load ; also, from condition (*a*) the acceleration imposed on the aircraft when the lift coefficient is changed slowly may be calculated. Consideration of (*b*) will show the effect of sudden change in lift coefficient on the normal acceleration experienced by the aircraft.

7. CONING ANGLE FOR MAXIMUM AXIAL LIFT WHEN $\ddot{\beta}_0 = 0$.

This is the condition when the blade has been accelerated to a coning angle (β_{M_1}) at which the flapping acceleration is zero and the resultant axial force acting on the aircraft is a maximum. This condition might

arise, say, if C_L momentarily increased and the blade coned and stabilised itself at a new angle without appreciable loss in rotational speed.
When $\ddot{\beta}_o = O$ equation 1 becomes

$$\mathcal{E}\beta_o = \frac{L \cos \beta_o}{W_b} = \frac{k_1 \cos^2\beta_o}{k3}\left[1 + \frac{k_2 \sin\beta_o (\omega R)^2}{gR}\right] \quad \ldots\ldots 2$$

The value of $\mathcal{E}\beta_o$ thus defined is a maximum when

$$\sin \beta_{M_1} = \frac{-2 + \sqrt{4 + 12\left[\frac{k_2 (\omega R)^2}{gR}\right]^2}}{\frac{6\, k_2 (\omega R)^2}{gR}} \quad \ldots\ldots 2\text{A}$$

Consideration of equation 2A shows that to a close order of approximation β_{M_1} is constant for all rotor sizes and tip speeds in which we are likely to be interested, *i.e.*,

$$\sin \beta_{M_1} = \frac{\sqrt{12}}{6} \text{ or } \beta_{M_1} = 35°$$

This means that any helicopter rotor is giving its maximum axial lift when coned at an angle of about 35°. This point may best be illustrated by an exaggeration, *i.e.*, a helicopter which can just lift itself when the rotor is coned to 35° can never carry more load because further increase in coning angle will not result in any increase in axial lift. It should be noted that 35° is not the best coning angle from the viewpoint of carrying maximum useful load—see para. 9 ; further, the power required to drive a rotor coned at 35° would be excessive.

The actual values of $\mathcal{E}\beta_o$ are dependent on the constants k_1, k_2 and k_3, and will vary as between blades of different design. It is thought, however, that these constants cannot vary greatly between different designs ; also that the general relationship may be studied by assuming the following mean values for these constants :—

$$k_1 = 0{\cdot}42$$
$$k_2 = 0{\cdot}56$$
$$k_3 = 0{\cdot}72$$

Using these assumed values for the constants the relationship between $\mathcal{E}\beta_o$ and β_o, as defined in equation 2, are plotted in Fig. 3 for various values of (ω R) and radius (R). The depreciation in $\mathcal{E}\beta_o$ as the size of the rotor increases and as ω R and coning angle decrease is apparent from this figure.

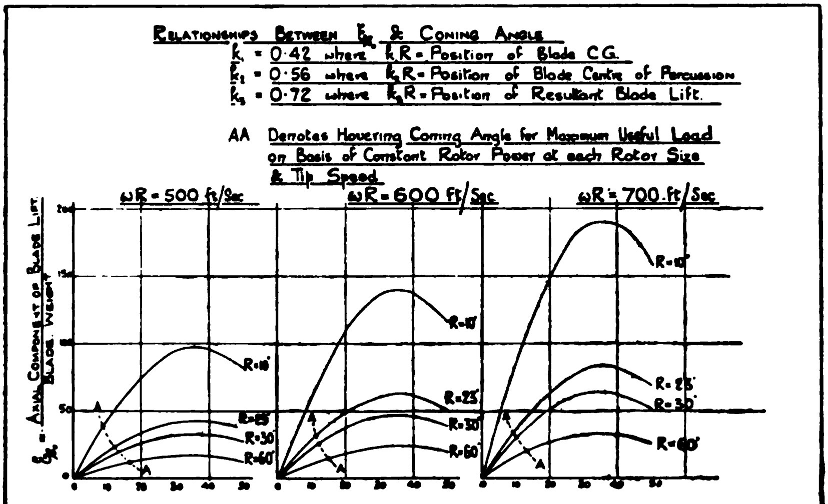


FIG. 3.

8. RELATIONSHIP BETWEEN THE BLADE WEIGHT/AIRCRAFT WEIGHT RATIO, ω R, RADIUS AND CONING ANGLE.

This relationship is derived from equation 2, which is the general equation relating blade weight to axial lift.

Since aircraft weight $\propto L_H \cos \beta_H$, it follows that :—

$$\frac{Wb}{W} = \frac{k_3}{k_1 \cos^2 \beta_H \left[1 + \frac{\sin \beta_H \, k_2 \, (\omega R)^2}{gR} \right]} \quad \ldots\ldots 3$$

To a close order of approximation

$$\frac{Wb}{W} = \frac{g \, k_3 \, R}{k_1 \, k_2 \cos^2 \beta_H \sin \beta_H \, (\omega R)^2} \quad \ldots\ldots \text{3A}$$

Using the previously assumed values for the constants k_1, k_2, k_3, expression 3A becomes

$$\frac{Wb}{W} = \frac{90 \cdot 8 \, R}{\cos^2 \beta_H \sin \beta_H \, (\omega R)^2} \quad \ldots\ldots \text{3B}$$

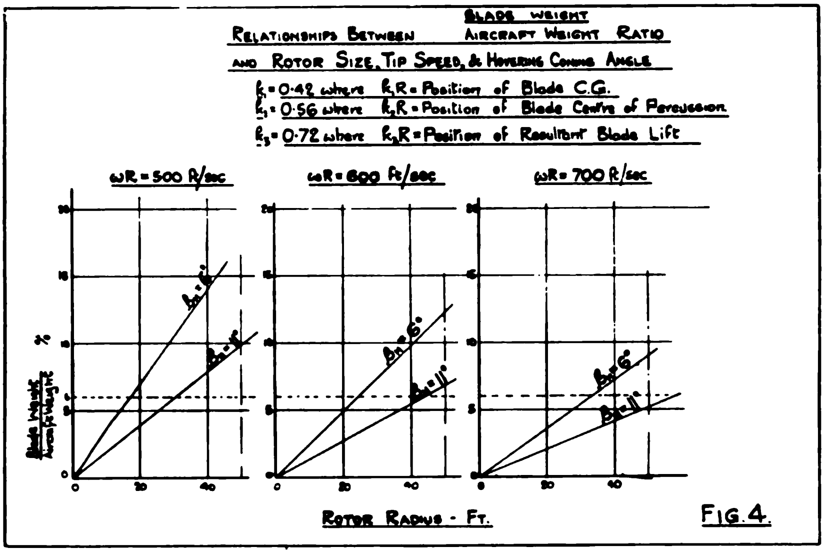
Expression 3B is plotted in Fig. 4 for various values of R, β_H and (ωR). It will be observed from this figure that economy in the $\frac{Wb}{W}$ ratio is achieved by working to large hovering coning angles and high tip speeds.

It is of interest to note from Fig. 4 that, if it were feasible from constructional considerations to build a blade of any size for a $\frac{Wb}{W}$ ratio of, say, 6%, and, if forward speed set a limit of, say, 600 ft./sec. to rotational tip speed, then

(*a*) the economical limit of rotor size would be 86 ft. when β_H is 11°,

and (*b*) the economical limit of rotor size would be 48 ft. when β_H is 6°.

The above follows, since larger sizes necessitate an increase in the $\frac{Wb}{W}$ ratio above the 6% figure.



9. BEST HOVERING CONING ANGLE FROM VIEWPOINT OF WEIGHT ECONOMY.

While expression 3 enables a study to be made of the effect of change in certain variables on the blade weight/aircraft weight ratio, it does not suggest what the hovering coning angle should be in order to achieve a high useful load. If we take any helicopter, and if we lighten the blades, but change nothing else except the payload, it follows that there must be some coning angle at which the payload is a maximum, because :—

(*a*) on the one hand, we are saving blade weight, part of which can appear as increased payload.

and (*b*) on the other hand, we are reducing the all-up-weight because we have not materially changed the length of the resultant lift vector, but we have given it a greater inclination and hence a smaller axial component which must result in a decrease in payload.

Hence, for constant engine power, increase in hovering coning angle has a twofold effect, namely, blade weight comes down, but so also does

the all-up-weight. It follows, then, that in order to achieve maximum weight economy the hovering coning angle should be so chosen that the difference between the all-up-weight and the sum of the blade weights is a maximum, *i.e.*,

$$W_A = W - zW_b \text{ should be a maximum.}$$

The coning angle which will satisfy this condition will obviously be dependent on what happens to the length of the resultant lift vector when the coning angle changes, but the rotor power does not. Because it would seem a reasonable assumption to make, and in the absence of more reliable information, the above argument is continued on the basis that the length of the resultant lift vector is constant for constant rotor power at all hovering coning angles in which we are likely to be interested.

Since,

$$W_A = W - zW_b$$

and $W = zL \cos \beta_H$ and $W_b = \dfrac{Wg\, k_3\, R}{k_1\, k_2 \cos^2\beta_H \sin \beta_H (\omega R)^2}$ from 3A

$$W_A = zL \left[\cos \beta_H - \frac{2g\, k_3\, R}{k_1\, k_2\, (\omega R)^2 \sin 2\beta_H}\right] \quad \ldots\ldots 4$$

The value of β_H which results in a maximum value of W_A can best be obtained graphically from equation 4. This is done in Fig. 5, using the previously assumed values for the constants k_1, k_2, and k_3, and various values of R and (ωR). The optimum hovering angles from the weight viewpoint thus obtained are included in Fig. 3, from which it will be observed that :—

(*a*) for any given rotor, increase in ωR results in a decrease in the value of best hovering coning angle from the overall weight viewpoint.

and (*b*) for any given ωR, increase in rotor size results in an increase in the value of the best hovering coning angle from the overall weight viewpoint.

A typical figure for the optimum hovering coning angle is 11° when R is 23 ft. and ωR is 600 ft./sec.

10. LOSS IN USEFUL LOAD WHEN A HOVERING CONING ANGLE OTHER THAN THE OPTIMUM FROM THE WEIGHT VIEWPOINT IS ADOPTED.

Consider the case when the helicopter blades are replaced by ones of like aerodynamic properties and mass distribution, but of different weight. Let the engine, transmission system and fuselage be unchanged. The power available at the rotor will then be constant, but the coning angle will change because of the change in blade weight.

On the grounds of the argument outlined in para. 9 there will be a best hovering coning angle from the viewpoint of achieving a maximum value of W_A. Since nothing in the fuselage is altered this best hovering

angle will result in a maximum value of useful load. Again, if a coning angle other than the best is chosen, W_A will decrease by an amount which must be subtracted from the useful load.

Let β_{H_1} be the best hovering coning angle, *i.e.*, the value of β_H which gives the maximum value of W_A is defined in equation 4.

Let the maximum value of W_A be $W_{A\,(max.)}$.

Let the maximum useful load be Wu (max.) $= xW_{A\,(max.)}$.

Let the hovering coning angle adopted be β_H.

Then the ratio of the useful load achieved to the maximum useful load is

$$\frac{W_u}{W_{u\,(max)}} = \frac{xW_{A\,(max)} - (W_{A\,(Max)} - W_A)}{xW_{A\,(max)}}$$

or, from equation 4.

$$\frac{W_u}{W_{u\,(max)}} = \frac{1}{x}\left\{\frac{k_1\,k_2(\omega R)^2 \cos\beta_H - 2gk_3\,R\,\mathrm{cosec}\,2\beta_H}{k_1\,k_2(\omega R)^2 \cos\beta_{H_1} - 2gk_3\,R\,\mathrm{cosec}\,2\beta_{H_1}} + x - 1\right\} \quad \ldots 5$$

In order to examine the variation in the $\frac{W_u}{W_{u\,(max.)}}$ ratio with hovering coning angle, equation 5 is plotted in Fig. 6 for rotors of 23 ft. and 30 ft. radius running an ωR of 600 ft./sec. The values of the constants k_1, k_2 and k_3 are as previously assumed and the maximum useful load achieved at the optimum hovering coning angle is taken as 0·25 W_A. It will be observed that under these conditions, which approximate to typical modern practice, and when R is 23 ft., the useful load at a 6° hovering angle is 94% of what it would be at the optimum hovering coning angle which is 11°. At a hovering coning angle of 4° $\frac{W_u}{W_{u\,(max.)}}$ drops to about 80%.

11. RELATIONSHIP BETWEEN HOVERING CONING ANGLE AND LIFT COEFFICIENT.

It will be appreciated that it is essential for the operator to be able to apply lift coefficients greater than the normal hovering lift coefficient for the purpose of catering for growth in all-up-weight, enabling the aircraft to accelerate, and to compensate for decrease in air density with increase in altitude. It is of interest to enquire what the relationship between coning angle and lift coefficient is under conditions when the blade has no acceleration about its flapping hinge, *e.g.*, say, when the all-up-weight changes.

This may be done as follows :—

From relationship (vi) of para. 5 it follows that

$$L \cos \beta_o \propto C_L \cos^3 \beta_o \;\&\; L_H \cos \beta_H \propto C_{L_H} \cos^3 \beta_H$$

From equation 2

$$L \cos \beta_o \propto \cos^2\beta_o \left[1 + \frac{k_2 \sin \beta_o(\omega R)^2}{gR} \right]$$

$$\& \; L_H \cos \beta_H \propto \cos^2\beta_H \left[1 + \frac{k_2 \sin \beta_H(\omega R)^2}{gR} \right]$$

Hence,

$$\frac{C_L}{C_{L_H}} = \frac{\cos \beta_H}{\cos \beta o} \left(\frac{1 + \dfrac{k_2 \sin \beta_o(\omega R)^2}{gR}}{1 + \dfrac{k_2 \sin \beta_H(\omega R)^2}{gR}} \right) \quad \ldots\ldots 6$$

Since at normal hovering coning angles the couple resulting from blade weight is small compared with the centrifugal couple, the expression may be simplified to a close order of approximation thus :—

$$\frac{C_L}{C_{L_H}} = \frac{\tan \beta_o}{\tan \beta_H} \quad \ldots\ldots 6A$$

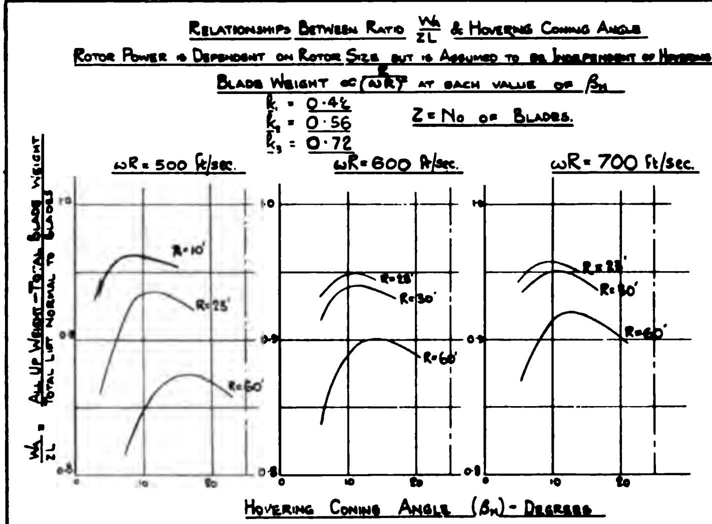


Fig. 5.

12. RELATIONSHIP BETWEEN AIRCRAFT NORMAL ACCELERATION AND BLADE LIFT.

In determining the influence of blade lift on the axial acceleration experienced by the aircraft it is desirable to consider the two conditions mentioned in para. 6, *i.e.*, $\ddot{\beta}_o = O$ and $\ddot{\beta}_o$ real. The first condition determines the aircraft axial loading when the blade has no acceleration about the flapping hinge but is displaced to some coning angle β_o greater than β_H. The second condition determines the aircraft axial loading while the blade is being accelerated from β_H to β_o. If the acceleration is of sufficient magnitude the blade will exceed β_o momentarily by an amount which may be sufficient to give rise to momentary accelerations appreciably in excess of the values determined by considerations of $\ddot{\beta}_o = O$.

In case (*a*) under, the case when $\ddot{\beta}_o = O$ is considered ; in case (*b*) under, the effect of making $\ddot{\beta}_o$ real is investigated. In both cases it is assumed that there is no loss in ω during the manoeuvre.

Case (*a*) when $\ddot{\beta}_o = O$.

Let N_{β_o} = vertical load factor when $\ddot{\beta}_o = O$.

Let $L \cos \beta_o$ = axial component of blade lift.

Let $L_H \cos \beta_H$ = axial component of blade lift during hovering.

$$N_{\beta_o} = \frac{L \cos \beta_o}{L_H \cos \beta_H} = \frac{C_L \cos^3 \beta_o}{C_{L_H} \cos^3 \beta_H} \text{ from relation (vi) of paragraph 5}$$

$$= \frac{\cos^2 \beta_o \left[1 + \dfrac{k_2 \sin \beta_o (\omega R)^2}{gR} \right]}{\cos^2 \beta_H \left[1 + \dfrac{k_2 \sin \beta_H (\omega R)^2}{gR} \right]} \text{ from equn. 2} \quad . \quad . \quad 7$$

Hence,

$$N_{\beta_{o(max)}} = \frac{C_{L_M} \cos^3 \beta_M}{C_{L_H} \cos^3 \beta_H} = \frac{\cos^2 \beta_M \left[1 + \dfrac{k_2 \sin \beta_M (\omega R)^2}{gR} \right]}{\cos^2 \beta_H \left[1 + \dfrac{k_2 \sin \beta_H (\omega R)^2}{gR} \right]} \quad . \quad 7A$$

For any given value of β_H the equivalent value of β_M can be found from 6A provided the ratio $\dfrac{C_{L_M}}{C_{L_H}}$ is known. Also, the most economical *value of* β_H can be found from equation 4.

When $\omega R = 600$ ft./sec., $R = 23$ ft. and the constants are as before, the most economical hovering coning angle is shown in para. 9 to be 11°. If $\frac{C_{L_M}}{C_{L_H}}$ is taken as 3, then, from equation 6A, β_M is 30° and, from equation 7A, N_{β_o} (max.) = 2·0. If the hovering coning angle is changed from 11° to 6° the equivalent value of N_{β_o} (max.) is 2·6. The relationship between N_{β_o} and β_o is shown graphically in Fig. 7 for the cases when $\beta_H = 6°$, $\beta_H = 11°$, $\frac{C_{L_M}}{C_{L_H}} = 3$, $R = 23$ft. and $\omega R = 600$ ft./sec.

Case (*b*) when $\ddot{\beta}_o$ is real.

When the blade is being accelerated about the flapping hinge it will be seen from Fig. 2 that the axial lift component is

$$\left(L \pm \frac{I\ddot{\beta}_o}{k_2 R} \right) \cos \beta_o$$

Hence, the axial load factor N

$$= \frac{\left(L \pm \frac{I\ddot{\beta}_o}{k_2 R} \right)}{W} \cos \beta_o \quad - 8A$$

From expression 1A.

$$\ddot{\beta}_o = \frac{\cos \beta_o\, g}{k_2 R} \left(\frac{k_3 L}{W_b k_1 \cos \beta_o} - 1 - \frac{k_2 \sin \beta_o (\omega R)^2}{gR} \right) \quad - 8B$$

By substituting the value of $\ddot{\beta}_o$ defined by 8B in equation 8A, it may be shown that

$$\frac{L \cos \beta_o}{W} = \frac{N - \frac{W_b}{W}\frac{k_3}{k_2} \mathcal{E}_{\beta_o}}{1 - k_3/k_2}$$

Since, from equation 2,

$$\frac{W_b \mathcal{E}_{\beta_o}}{W} = \frac{L \cos \beta_o}{W} \quad N_{\beta_o}$$

and since,

$$\left. \begin{array}{l} W \propto L_H \cos \beta_H \propto C_{L_H} \cos^3 \beta_H \\ \& \; L \cos \beta_o \propto C_L \cos^3 \beta_o \end{array} \right\} \text{from relation (vi) of paragraph 5}$$

it follows that

$$\frac{C_L \cos^3 \beta_o}{C_{L_H} \cos^3 \beta_H} = \frac{N - N_{\beta_o} k_3/k_2}{1 - k_3/k_2}$$

$$\text{i.e.} \quad N = \frac{C_L \cos^3 \beta_o}{C_{L_H} \cos^3 \beta_H} - k_3/k_2 \left(\frac{C_L \cos^3 \beta_o}{C_{L_H} \cos^3 \beta_H} - N_{\beta_o} \right) \quad (8)$$

In equation 8 $\frac{C_L}{C_{L_H}}$ denotes any change in lift coefficient which the operator chooses to select instantaneously at any coning angle β_o and is not necessarily the value, defined by equation 6, required for static equilibrium. Also, in equation 8, N_{β_o} is the load factor imposed on the aircraft by virtue of coning angle alone, *i.e.*, as defined by equation 7. The above may be followed more clearly by assuming that during hovering C_{L_H} is suddenly increased to C_{L_M}. Then the instantaneous value of N becomes

$$N = \frac{C_{L_M}}{C_{L_H}} - k_3/k_2 \left(\frac{C_{L_M}}{C_{L_H}} - 1 \right)$$

However, as the coning angle increases to some angle β_o greater than β_H, because of the blade's upward acceleration about the flapping hinge, the axial load factor becomes :—

$$N = \frac{C_{L_M} \cos^3 \beta_o}{C_{L_H} \cos^3 \beta_H} - k_3/k_2 \left(\frac{C_{L_M} \cos^3 \beta_o,}{C_{L_H} \cos^3 \beta_H} - N_{\beta_o} \right)$$

where N_{β_o} is as defined by equation 7.

Using our usual assumed values for the constants and a $\frac{C_{L_M}}{C_{L_H}}$ ratio of 3, the relationship between N and β_o, as defined by equation 8, is plotted on Fig. 7.

Also plotted on Fig. 7 is the relationship between N_{β_o} and β_o, as defined by equation 7. It will be seen from Fig. 7 that at coning angles less than β_M sudden increase in blade lift may give momentary relief to the aircraft as compared with the case when the increase in blade lift is made slowly. The extent of the relief is dependent on the relative positions of the blade centre of pressure and centre of percussion $\frac{(k_3)}{(k_2)}$. When the blade overshoots the equilibrium position and is being retarded there may be an increase in axial loading caused by the reversed sense of the inertia term. In order to

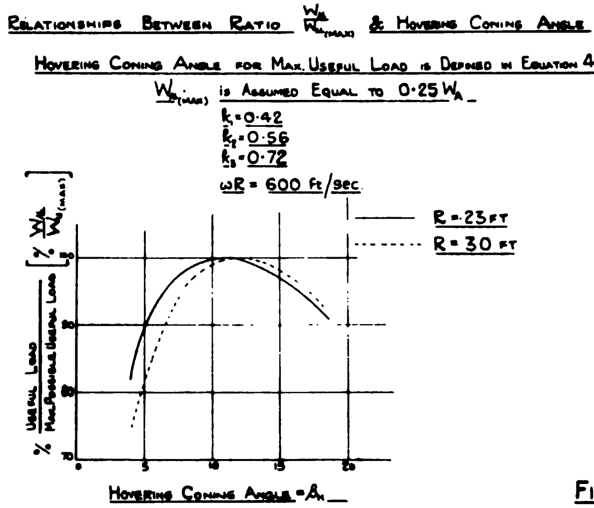


FIG. 6

determine the maximum value of N it is necessary, then, to determine if the expression 8 reaches a maximum before or after the blade has reached its maximum angle of flap resulting from acceleration.

The maximum coning angle resulting from acceleration may be obtained by equating the gain in kinetic energy of the blade during acceleration about the flapping hinge to its loss in kinetic energy during retardation.

In general terms the gain in K.E. is $\frac{1}{2}I\dot{\beta}_o^2$.

From expression 1A

$$\ddot{\beta}_o = \frac{g}{k_2 R}\left(\frac{k_3\, LW}{k_1\, W_b W} - \cos\beta_o - \frac{k_2 \cos\beta_o \sin\beta_o (\omega R)^2}{gR}\right)$$

From the fundamental relationship between velocity, distance, and acceleration (i.e. $\dot{\beta}_o^2 = 2\ddot{\beta}_o \beta_o$),

$$\dot{\beta}_o^2 = 2\int_{\beta_1}^{\beta_2} \ddot{\beta}_o \, d\beta_o \quad \ldots\ldots \text{(a)}$$

Obviously, $\dot{\beta}_o = O$ when $\beta_o = \beta_H$ and $\dot{\beta}_o$ is a maximum when $\beta_o = \beta_M$. Hence, since $W \propto C_{L_H} \cos^3 \beta_H$.

$$KE_{(max.)} = W_b k_1 R \int_{\beta_H}^{\beta_M}\left(\frac{k_3 C_L \cos^2\beta_o\, W}{k_1 C_{L_H} \cos^3\beta_H\, W_b} - \cos\beta_o - \frac{k_2\cos\beta_o \sin\beta_o (\omega R)^2}{gR}\right) d\beta_o$$

Let the blade reach a maximum coning angle during retardation of β_F which is greater than β_M. Then the loss in blade K.E.

$$= \tfrac{1}{2} I \int_{\beta_M}^{\beta_F} -\ddot{\beta}_0 \, d\beta_0$$

Equating the energy gain to the energy loss it follows that

$$\frac{k_3 W_{C_L} \left(\beta_F - \beta_H + \tfrac{1}{2}(\sin 2\beta_F - \sin 2\beta_H)\right) + \sin\beta_H - \sin\beta_F}{2 k_1 W_b C_{L_H} \cos^3 \beta_H} + \frac{k_2(\omega R)^2 (\cos 2\beta_F - \cos 2\beta_H)}{4gR} = 0 \; \ldots\ldots \; 9.$$

When $\dfrac{C_L}{C_{L_H}} = 3$, $\beta_{H_1} = 11°$, $\omega R = 600$ ft./sec., and $R = 23$ ft., it follows from equation 3 that $W/W_b = 33$, and equation 9 becomes

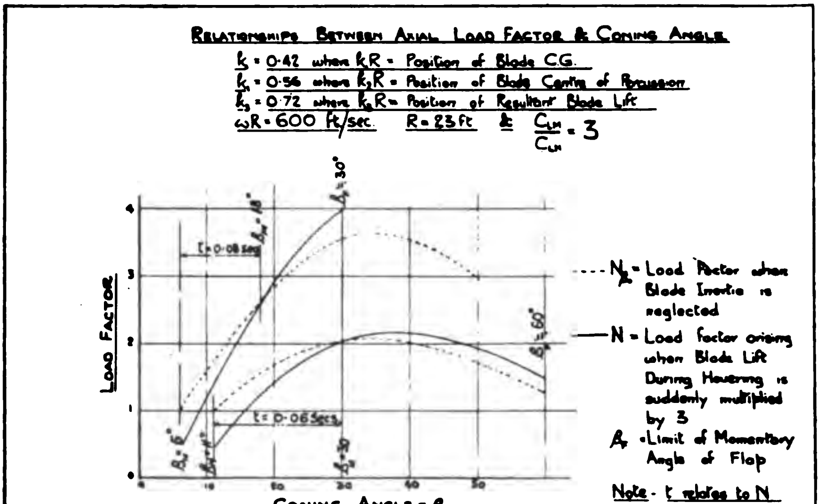
$$\beta_F + \tfrac{1}{2}\sin 2\beta_F + \cdot 765 \cos 2\beta_F = 1{\cdot}089, \quad — \quad 9A$$

which is satisfied when $\beta_F = 60°$.

When $\dfrac{C_L}{C_{L_H}} = 3$, $\beta_H = 6°$, $\omega R = 600$ ft./sec., and $R = 23$ ft., it follows from equation 3 that $\dfrac{W}{W_b} = 17$, and equation 9 becomes

$$\beta_F + \tfrac{1}{2}\sin 2\beta_F + 1{\cdot}57 \cos 2\beta_F = 1{\cdot}739 \quad — \quad 9B.$$

which is satisfied when $\beta_F = 30°$.



- Fig 7 -

— By comparing the above values of β_F with Fig. 7 it will be seen that the maximum values of N are 2·2 and 4 when β_H is 11° and 6° respectively. Thus, it can be concluded that the effect of not working to the optimum blade weight is twofold since, in addition to loss in useful load, the aircraft is liable to experience higher normal accelerations for the same value of the $\dfrac{C_L}{C_{L_H}}$ ratio.

13. RELATIONSHIP BETWEEN TIME, ROTOR ANGULAR DISPLACEMENT AND ANGLE OF FLAP.

It is of interest to know the order of the time taken for the blade to move from its equilibrium position at one value of C_L to its equilibrium position at another.

The fundamental relationship is

$$\dot{\beta}_o = \ddot{\beta}_x \, t$$

where $\ddot{\beta}_x$ is the average acceleration over the angular displacement from the blade's position of rest to the position when the velocity is $\dot{\beta}_o$.

Hence,

$$\ddot{\beta}_x = \frac{\int_{\beta_1}^{\beta_2} \ddot{\beta}_o \, d\,\beta_o}{\beta_2 - \beta_1}$$

and using relation (*a*), on page 20,

$$t = \frac{\sqrt{\int_{\beta_1}^{\beta_2} \ddot{\beta}_o \, d\,\beta_o \, (\beta_2 - \beta_1 2)}}{\int_{\beta_1}^{\beta_2} \ddot{\beta}_o \, d\,\beta_o}$$

i.e.,

$$t = \frac{\sqrt{2}\,(\beta_2 - \beta_1)}{\sqrt{\int_{\beta_1}^{\beta_2} \ddot{\beta}_o \, d\,\beta_o}}$$

Hence, in general terms, the time taken for the blade to move from coning angle β_1, to coning angle β_2 under acceleration $\ddot{\beta}_o$ as defined by equation 8B is

$$t = \frac{\sqrt{2}\,(\beta_2 - \beta_1)}{\sqrt{\dfrac{g}{k_2 R}\left[\dfrac{k_3 W C_L(\beta_2 - \beta_1 + \frac{1}{2}(\sin 2\beta_2 - \sin 2\beta_1))}{2 k_1 W_b C_{L_H} \cos^3\beta_H} - \sin\beta_2 + \sin\beta_1 + \dfrac{k_2(\omega R)^2(\cos 2\beta_2 - \cos 2\beta_1)}{4gR}\right]}} \quad - \quad 10$$

If the number of revolutions made by the rotor in time $t = n$, then

$$n = \frac{\omega t}{2\pi} \cdot \ldots \ldots \quad 11$$

where t is as defined in equation 10.

Using relations 10 and 11 it follows that when $\beta_1 = \beta_H = 11°$, when $\beta_2 = \beta_M = 30°$, when $\frac{C_{L_M}}{C_{L_H}} = 3$, $\omega R = 600$ ft./sec., and $R = 23$ ft., the time taken for the blade to move from the hovering coning angle to β_M is about 0·06 sec., and the corresponding angular rotor displacement is about $\frac{1}{4}$ REV. The equivalent figures when $\beta_1 = 6°$ and $\beta_2 = 18$ are 0·08 sec. and $\frac{1}{5}$ REV. respectively. The effect of air damping is neglected in the calculations and this will lead to a slight underestimate of $\underline{t}$ and $\underline{n}$.

PART 2.

14. PROBABLE RELATIONSHIPS BETWEEN ROTOR SIZE, MAXIMUM USEFUL LOAD AND PERCENTAGE USEFUL LOAD.

It is obvious that the total load which any blade can support is the vertical component of its axial lift, *i.e.*, $L \cos \beta_0$.

In the hovering case the vertical component of rotor axial lift $zL_H \cos \beta_H$) must overcome the weights of the various parts which constitute the aircraft, *i.e.*, the blades, transmission, engine and power plant, airframe, tail rotor (if any), crew weight and useful load. If we knew how all these aircraft parts except useful load varied with rotor size we could equate them to $L_H \cos \beta_H$ and study the variation in useful load with rotor size. Since we do not know exactly how these quantities vary with rotor size it is necessary to assume possible ways in which they might vary and in the following treatment this is done in the belief that, even should the assumptions be wrong, the overall method adopted is correct and therefore capable of application when reliable data about component weight variation with rotor size are available.

Let us now consider what the various major aircraft components are and how they might vary with rotor size if, say, we keep the disc loading and tip speed constant.

MAJOR COMPONENT.	ASSUMPTION.
W_{T_1} = That part of the transmission the weight of which must be dependent on rotor torque.	Part of the transmission must run at rotor speed, while the speed of the remainder of the transmission can be varied by suitable gearing to counter torque and weight increase with growth in rotor size. The manner in which the weight of the transmission running at rotor speed varies with varying rotor radius is not very clear, however, there seems to be an indication that $\frac{W_{T_1}}{W}$ varies as the square of the rotor size. In the absence of more complete data this law will be assumed, but the limitations of the basis of the assumption should be borne in mind when examining the results which the expressions to be derived will show for useful load and percentage useful load.
W_{T_2} = that part of the transmission the weight of which can be made independent of rotor torque.	Part of the transmission need not run at rotor speed and hence need not be subjected to rotor torque because angular speed variation can be used to counter growth in torque and weight. In the absence of more accurate data, $\frac{W_{T_2}}{W}$ is assumed to be constant for all values of rotor size.
W_E = engine and power plant.	W_E is dependent on the power requirements of the rotor and the power/weight ratio of the engine. For constant tip speed and disc loading the power requirements of the rotor may be shown to be proportional to the aircraft weight. Hence, since the power/weight ratio of conventional engines is more or less constant, $\frac{W_E}{W}$ can be taken as constant for rotors of different size, but having the same tip speed and disc loading. $\frac{W_E}{W}$ is then assumed to be constant when the tip speed and the disc loading are constant.

MAJOR COMPONENTS.		ASSUMPTIONS.
W_F	= airframe, including landing gear, furnishings, etc.	For any given configuration, W_F is likely to be proportioned to the all-up-weight. $\frac{W_F}{W}$ is then assumed to be constant.
W_b	= Main rotor blades.	W_b has been studied in Part 1 of this paper and it is shown in equation 3A that $\frac{W_b}{W}$ is proportional to $\frac{R}{(\omega R)^2}$ for constant coning angle.
W_{b_T}	= Tail rotor blades.	W_{b_T} will vary with R because the lift required from the tail rotor blades will vary with the main rotor torque in order to achieve balance. Exact treatment would show $\frac{W_{b_T}}{W}$ to obey a law similar to equation 3. However, in practice, the tail rotor usually operates at such a low coning angle that any weight increase could be offset by a slight increase in coning angle. Hence, it is assumed that $\frac{W_{b_T}}{W}$ can be regarded as constant for all values of R in which we are likely to be interested.
W_c	= Crew weight.	W_c is charged to the aircraft tare weight because this weight cost must be met before the aircraft can be operated and, hence, it is as much a part of the aircraft as any other essential component. W_c will not vary with rotor size, but will depend only on the number of crew members carried. Hence, W_c can be taken as constant if we assume, say, only one crew member. $\frac{W_c}{W}$, however, is not constant.
W_u	= Useful load including fuel, oil, freight, passengers, but excluding crew.	$W_u = W - W_{T_1} - W_{T_2} - W_E - W_F - W_b - W_{b_T} - W_c$

Now, $W = W_{T_1} + W_{T_2} + W_E + W_F + W_b + W_{b_T} + W_c + W_u$ ——12

On the basis of the above assumptions, equation 12 may be re-written thus :—

$$\frac{W_u}{W} = 1 - \frac{(W_{T_2}+W_E+W_F+W_{b_T})}{W} - C_1R^2 - \frac{C_2R}{(\omega R)^2} - \frac{W_c}{\pi R^2 DL} \quad - 12A$$

$$\text{and } W_u = \pi R^2 DL\left[1 - \frac{(W_{T_2}+W_E+W_F+W_{b_T})}{W} - C_1R^2 - \frac{C_2R}{(\omega R)^2} - \frac{W_c}{\pi R^2 DL}\right] \quad - 12$$

where C_1 and C_2 are constants.

From 12A, it will be observed that the ratio $\frac{W_u}{W}$ has a turning value which can best be obtained by using the appropriate values of the constants and plotting the ratio against the variable R.

From equation 12B, it can be shown that for constant ωR and DL, W_u is a maximum when :—

$$R = \frac{-\frac{3C_2}{(\omega R)^2} + \sqrt{\left[\frac{3C_2}{(\omega R)^2}\right]^2 + 32C_1\left[1 - \frac{W_{T_2}+W_E+W_F+W_{b_T})}{W}\right]}}{8C_1} \quad - 12C$$

In considering equations 12A, B and C, in the light of the assumptions made above, it will be observed that $\frac{W_E}{W}$ is only constant when the tip speed and disc loading are constant ; also, in deriving the expression β_H has been assumed constant. Hence, general deduction by the application of a set of numerical values for the constants in these equations is not possible. However, for a given set of values for tip speed, disc loading and hovering coning angle $\frac{W_u}{W}$ and W_u can be calculated. This has been done for an ordinary commercial type helicopter designed to achieve a top speed of about 150 m.p.h. and having a disc loading of 3 lbs./ft.^{2}, a tip speed of 600 ft./sec., and hovering coning angles of 6° and 11°. The results are shown on Fig. 8 and are based on the following values for the constants :—

$\frac{W_{T_1}}{W}$ = 8% when R is 23 ft., which results in a value of $C_1 = \frac{1 \cdot 54.}{10^4}$

$$\frac{W_{T_2} + W_E + W_F + W_{b_T}}{W} = 0 \cdot 6$$

$\frac{W_b}{W}$ = 6% when ωR = 600 ft./sec. and R = 23 ft., which leads to a value of C_2 = 945 when β_H = 6° and 657 when β_H = 11°.

W_c = 200 lbs.

It will be observed that the following results are obtained for our commercial type helicopters having one crew member, a disc loading of 3 lbs./ft.^{2} and an ωR of 600 ft./sec. :—

(*a*)	(i) Rotor size for maximum useful weight lifted when $C_2 = 945$ ($\beta_H = 6°$)	=	60 ft. dia.
	(ii) Equivalent useful load	=	1,350 lbs.
	(iii) Equivalent aircraft weight	=	8,460 lbs.
	(iv) Equivalent percentage useful load	=	15·9%
(*b*)	(i) Rotor size for maximum useful weight lifted when $C_2 = 657$ ($\beta_H = 11°$)	=	64 ft. dia.
	(ii) Equivalent useful load	=	1,560 lbs.
	(iii) Equivalent aircraft weight	=	9,700 lbs.
	(iv) Equivalent percentage useful load	=	16·2%
(*c*)	(i) Rotor size for maximum percentage useful load when $C_2 = 945$ ($\beta_H = 6°$)	=	35 ft. dia.
	(ii) Equivalent percentage useful load	=	24%
	(iii) Equivalent aircraft weight	=	2,900 lbs.
(*d*)	(i) Rotor size for maximum percentage useful load when $C_2 = 657$ ($\beta_H = 11°$)	=	36 ft. dia.
	(ii) Equivalent percentage useful load	=	25%
	(iii) Equivalent aircraft weight	=	3,100 lbs.

It should be noted that the useful load relationships (W_u) shown in Fig. 8 are largely dependent on the value of the constant C_1. Since this constant reflects the weight penalty in the transmission, the curves are only meant to be applicable to machines of conventional design and are not applicable to aircraft of the type in which power is supplied from jets at the blade tips. One would expect the maximum useful load to be obtained with a larger diameter rotor with tip jet blades because of the simplified and lighter transmission.

It should be noted also that the maximum value of the percentage useful load relationship is dependent on the crew weight charge ; so also is the equivalent value of rotor size.

While the above assumed quantities influence the numerical results obtained they do not influence the method used which presumably will be capable of greater accuracy when more design information on the constants becomes available.

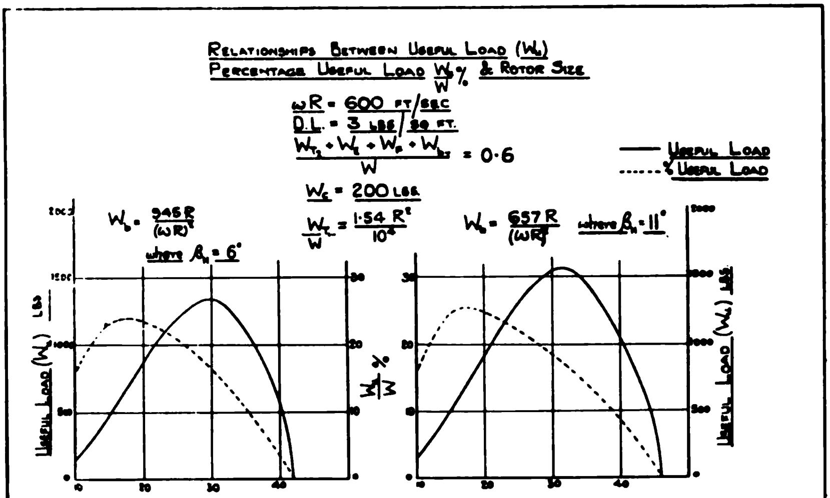


Fig. 8

15. Conclusions.

The broad conclusions arrived at and outlined under are based on the assumptions made and given in paragraphs 4 and 14.

(*a*) The coning angle at which the component of axial lift is a maximum is approximately 35° and, within all practical considerations, is independent of rotor diameter and tip speed.

(*b*) To a first order of approximation the ratio of blade weight to aircraft weight is proportional to the rotor radius, inversely proportional to the tip speed squared and inversely proportional to the product of the sine and cosine squared of the hovering coning angle. While maximum economy in blade weight is obtained by adopting the largest possible coning angle it does not follow that very large hovering coning angles result in maximum useful load.

(*c*) For any given rotor to achieve maximum useful load, a compromise must be struck between the saving in blade weight and the loss in the total axial component of lift (aircraft weight) as the coning angle increases. On the basis that, for constant rotor power the length of the resultant lift vector is independent of hovering coning angle, optimum hovering coning angles from the weight viewpoint can be calculated for all rotors.

These angles

(i) will decrease if ωR is increased and size is kept constant;

(ii) will increase if the size of the rotor is increased and ωR is kept constant.

On the above basis, a typical figure for the optimum hovering coning angle is 11° when R is 23 feet and ωR is 600 ft./sec.

(*d*) The values of maximum aircraft axial acceleration imposed by an articulated rotor system are dependent on the relative positions of the resultant blade lift vector and the centre of percussion of the blade, and are a minimum when the centre of lift is as far inside the centre of percussion as possible. If the optimum coning angle for useful load is chosen (see (*c*) above), a sudden increase in blade lift coefficient of 200% results, for blades having the assumed positions of centre of gravity, centre of percussion and centre of resultant lift, in momentary maximum axial accelerations of about 2 g when ωR is 600 ft./sec. and R is 23 ft. The maximum momentary angle of flap is about 60° and the blade equilibrium position at maximum C_L is 30°

If a weight penalty is paid in the blades and a coning angle of, say, 6° adopted during hovering the equivalent momentary acceleration is 4·0g. The maximum momentary angle of flap is 30° and the blade equilibrium position is 18° at maximum C_L. It follows that the effect of not adopting the optimum coning angle is twofold since, in addition to losing useful load, the aircraft is liable to experience a higher axial acceleration for the same increase in lift coefficient. The heavier rotor will, however, make the aircraft more manoeuverable.

(*e*) The time taken for the blades to move from one position of equilibrium to another when the blade lift is changed is very short. For rotors of the type with which we are familiar the time taken for displacement from the hovering coning angle to the coning angle corresponding to maximum C_L is shown to be less than 1/10th sec. if the effect of air damping on the blade is ignored.

(*f*) There would seem to be limits to the sizes of rotors and these limits are dependent on the tip speed, hovering coning angle, disc loading and the structural efficiency of the aircraft design. On the basis of very limited experience and on the assumptions that the tip speed is 600 ft./sec., the disc loading is 3 lbs./ft.^{2} and 200 lbs. of crew weight is charged to each rotor,

(i) the rotor size for maximum percentage useful load appears to be about 35 ft. dia. and the equivalent values of percentage useful load and aircraft weight are about 24% and 2,900 lbs. respectively ;

(ii) the rotor size for maximum useful load appears to be about 60 ft. dia. and the equivalent values of percentage useful load and aircraft weight are about 16% and 8,500 lbs. respectively.

The above values assume a single rotor configuration and part of the ratio of the transmission weight to the aircraft weight to vary as the square of the rotor radius. Since the latter assumption can at best only approximate to the truth, the values quoted above should be regarded only as indicating the possible order of things, rather than absolute quantities. Further, they are not relevant to jet driven blades.

MR. O. L. L. FITZWILLIAMS' VOTE OF THANKS TO MR. MCCLEMENTS.

MR. CHAIRMAN, FELLOW MEMBERS AND GUESTS,—I have accepted with pleasure our chairman's invitation to propose a vote of thanks to MR. MCCLEMENTS for the lecture he has just given us. I had expected to refer to him as reading his paper but I would like to call your attention to the rather extraordinary fact that this, the most difficult paper to which we have listened, is the first which has been presented without actually being read.

In any case it is obvious that MR. MCCLEMENTS' presentation of his lecture is the culmination of a long and painstaking effort, and for this he is certainly entitled to our fullest thanks. But he is also entitled to the thanks of everybody else interested in rotating wings, because he has presented a subject of fundamental importance in a manner which ensures that the major part of his paper will be included in all future text books on the design of rotating-wing aircraft.

Moreover MR. MCCLEMENTS has today played a star part in an occasion of great significance in the development of our Association.

For one thing, we have today listened for the first time to a paper of a specifically research nature, and by this I mean an original essay in pure knowledge, conceived and executed for the purpose of study, as distinct from the more usual kind of lecture which is generally an account of past thoughts and actions, mostly undertaken to overcome practical difficulties. It is hardly necessary for us to be reminded that the influence and prestige of a professional Association such as our own, must depend at least partly, on the ability of its members to produce, to understand and to use the essays of this kind.

Secondly, our Association is not only a convenient meeting place for old friends, it is also a sounding board for the knowledge and perhaps more important, the personalities of its members.

MR. MCCLEMENTS, like most of us, is relatively unknown by comparison with our previous lecturers, all of whom had world-wide reputations even before the War. In speaking this afternoon, he has fulfilled an important object of our Association in introducing himself to us and, through our Journal, to the world, as a new figure in the field of rotating wing aircraft development and also as an encouraging example of the persistance and ability upon which we base our confidence in the future of rotating wings in Great Britain.

MAC. has done us a great favour and I know that I have your support in offering him our thanks.

NINTH LECTURE

American Helicopter Development

By MAJOR JOHN SILTANEN, U.S.A.A.F.

A lecture presented to he Helicopter Association of Great Britain on Saturday, 24th January, 1948, at Manson House, 26 Portland Place, London, W.1.

Members who were fortunate enough to be able to attend the Association's Meeting on January 24th were rewarded by a most illuminating lecture on American Helicopter Development, delivered by MAJOR J. C. SILTANEN of the U.S.A.A.F.

MAJOR SILTANEN is here in the capacity of Air Technical Liaison Officer to the U.S. Military Attache in London ; in America he was engaged on work with the Rotary-wing Branch at Wright Field, being closely concerned with the military development of Sikorsky Helicopters.

The lecture took the form of an informal discourse illustrated by many interesting slides, most of which have since been published in the Aeronautical Press, receiving due credit. In token of the esteem in which we hold MAJOR SILTANEN, the Council have elected him an Honorary Member during his term of office in this country.

EIGHTH LECTURE

Some Aerodynamic Problems of the Helicopter

By H. B. SQUIRE, M.A. (Oxon.).

A lecture presented to The Helicopter Association of Gt. Britain on Saturday, 6th December, 1947, at Manson House, 26 Portland Place, London, W.1.

H. A. MARSH, A.F.C., A.F.R.Ae.S., IN THE CHAIR

INTRODUCTION BY J. A. J. BENNETT, D.SC., F.R.Ae.S.

I have accepted with pleasure the Chairman's request to introduce our lecturer this afternoon. It is twelve years ago since MR. SQUIRE proved himself to be a worthy successor to the late MR. H. GLAUERT at the Royal Aircraft Establishment in analysing the basic aerodynamic problems of the helicopter. The work of GLAUERT had been confined to vertical flight and to horizontal flight with the rotor axis vertical (like that of the Gyrodyne). MR. SQUIRE extended the analysis to the flight of a helicopter in which the propulsive force for horizontal flight was obtained by a forward inclination of the rotor axis. The classic report by MR. SQUIRE on this subject was studied closely by the Sikorsky organisation and was put into practical effect a few years later in the well-known Sikorsky designs.

MR. SQUIRE is recognised as the leading aerodynamicist on helicopters in this country and is Chairman of the Helicopter Committee of the Aeronautical Research Council. We are all looking forward to hearing from him this afternoon on certain aerodynamic problems of the helicopter which have remained a mystery to most of us until now.

MR. H. B. SQUIRE.

This lecture is concerned largely with the velocities induced by a helicopter rotor due to the aerodynamic forces on the blades and the influence of these velocities on the stability of multi-rotor helicopters. These questions are likely to become more important in the future than they are today and an understanding of them will help to elucidate some of the outstanding problems of the helicopter.

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THE VELOCITY FIELD OF A ROTOR.

GENERAL.

The helicopter rotor provides the lift which supports the weight of the aircraft, and to do this it must transmit momentum to the air in a downwards direction. In general, the rotor axis is inclined to the vertical and the rotor thrust is inclined forwards. Further, to obtain a horizontal component of the thrust air must be accelerated backwards. Thus we see that the air passing through the rotor is directed backwards and downwards as a direct consequence of the existence of the rotor thrust (Fig. 1). This extra speed which the air acquires is called the induced velocity.

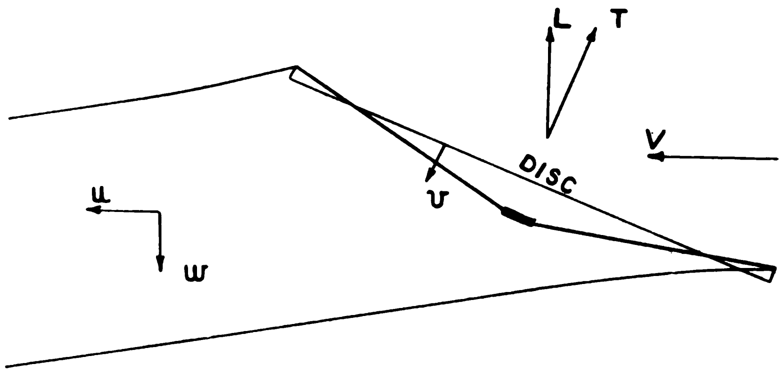

Fig. 1. *Crown copyright reserved.*

The order of magnitude of this induced velocity can be estimated purely from considerations of the conservation of momentum but the calculation of the exact distribution of induced velocity is a complicated problem. I should therefore show that this is worth doing before I proceed to describe the results of our recent work. The justifications for such an investigation are :—

(1) Analogy with allied aerodynamic problems of wing theory and propeller theory, which have progressed very far, suggests that detailed theories would be useful also for rotors.

(2) Elaborate theories of blade motion have been constructed based on crude assumptions as to the induced velocity distribution over the rotor disc : a better method of calculation of the induced velocity distribution would enable the blade motion theory to be more soundly based.

(3) The advent of the multi-rotor helicopter has shown that we need to know the induced velocity in order to calculate rotor interference effects.

ORIGINAL INVESTIGATIONS OF GLAUERT AND LOCK.

It is well worth while to study the original investigations of GLAUERT[1] and LOCK[2] on the autogyro, both from their historical interest and practical applicability. Glauert introduced the physical principles which are still

used but a number of difficulties remained, some of which were cleared up by LOCK in his subsequent investigation. Two major assumptions were introduced by Glauert to enable him to carry through this analysis. These were :—

(1) *Induced velocity*.—He assumed for the major part of his investigation that the induced velocity associated with the rotor lift force is uniform and directed along the axis of the rotor. Some of the consequences of assuming that the induced velocity varied linearly from front to rear of the rotor were also considered ; this latter kind of induced velocity field might be expected from wing theory which suggests that upwash would be present at the front of a rotor and downwash behind. But there is no simple way of specifying the fore and aft variation of the induced velocity and this alternative proposal of Glauert has not been generally followed. The assumption of a uniform induced velocity on the other hand led to definite conclusions when linked with Glauert's second assumption.

(2) *The momentum equation* is assumed to be of the form

$$T = \rho\pi R^2 V' \, . \, 2v, \qquad (1)$$

where T = the thrust.
R = the radius of the disc.
V' = the resultant velocity at the disc.
v = the induced velocity at the disc, so that V' is the velocity obtained by combining the air velocity V and the induced velocity v.

This formula is a generalisation of the two extreme cases :—

(*a*) The Froude momentum equation for axial flow. In this case V and v are both directed along the axis of the rotor so that

$$V' = V + v$$

and $$T = \rho\pi R^2(V + v)2v$$

(*b*) The relation for elliptic loading on a wing of span $2R$ at small incidence. In this case the induced velocity v is normal to the stream velocity V and is small compared with it. It is known that the lift of the wing L is then related to the induced velocity v by the formula

$$L = \rho\pi R^2 V.2v$$

It will be seen that equation (1) reduces to this form if we may replace the resultant velocity V' by the stream velocity V. Thus we see that GLAUERT'S momentum equation for the thrust is a generalisation of two limiting cases and this is its only real justification.

LOCK started from the framework prepared by GLAUERT but he carried through the analysis of the aerodynamic characteristics and the blade motion much more thoroughly so that the nature of the approximations was clear at every stage. The result is that his report is still a standard reference work. However, he was forced to adopt the assumption of a uniform induced velocity for lack of any reliable theory of the induced velocity distribution and this is the main gap in his work.

It is worth while to start briefly with the exact problem and consider stage by stage what approximations are introduced into our analysis. The first approximation that we make is the restriction to a linearised theory, *i.e.*, we assume that the induced velocities are all small compared with the stream velocity. This is permissible provided that the thrust coefficient C_T, defined by the equation

$$C_T = \frac{2T}{\rho V^2 \pi R^2},$$

is not too large. The linearised theory is probably valid up to $C_T = 0.5$ approximately.

The next steps in the approximation are to ignore the rotation in the slipstream and to assume that there are sufficient blades to permit neglect of the periodicity in the flow. The latter assumption is a drastic one but is essential since we already know that the solution of the axial flow propeller with a finite number of blades is very difficult : the corresponding case of an oblique propeller with a finite number of blades is probably insoluble.

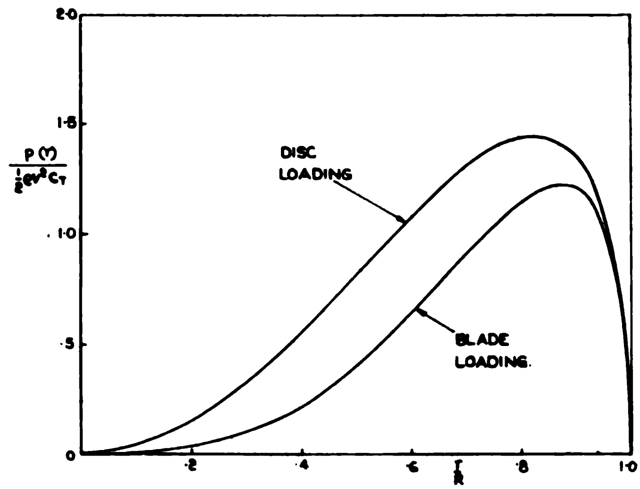

Fig. 2. Assumed Loading Distribution.

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We have now reduced our problem to a disc loading problem : we have a thrust T which is distributed over a disc of radius R. The disc we define as the plane from which the path of the blade tips deviates as little as possible. In addition to the thrust which is assumed to act normal to this reference plane there may be small forces in the plane of the disc, but these are in practice less than 5% of the thrust and may be ignored in considering the induced velocity field. We may further assume that for a rotor with hinged blades and small hinge offset the thrust T acts through the centre of the disc since otherwise there would be a rolling or pitching moment present at the hub. We are, therefore, led to the assumption that the loading is symmetrical round the disc ; this is certainly not more than a rough approximation but it may be possible to improve it in the future. We further know

that the lift vanishes at the root and at the tips of the blades, *i.e.*, the load vanishes at the centre and at the rim of the disc. There is one particular load distribution which satisfies these conditions for which it is not too difficult to make calculations. This is for the loading over the disc given by

$$p(r) = \frac{15}{8}\rho V^2 \left(\frac{r}{R}\right)^2 \sqrt{1-\left(\frac{r}{R}\right)^2} C_T \qquad \ldots\ldots (2)$$

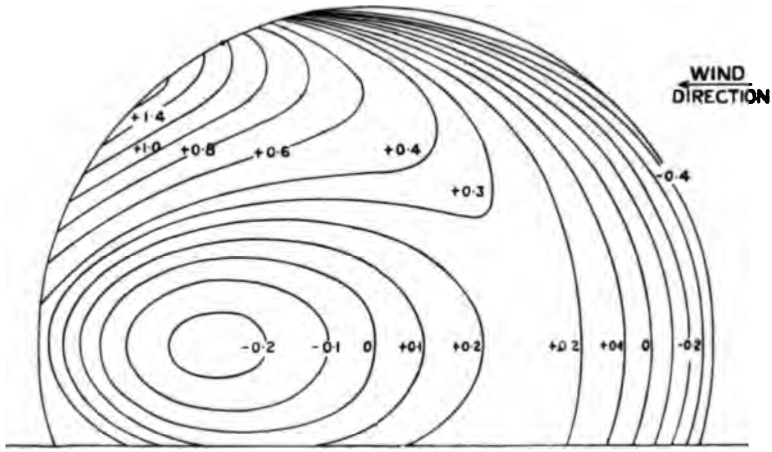
This is shown in Fig. 2 and is the loading assumed for all the induced velocity calculations. The corresponding load distribution along a blade is

$$l(r) \propto \left(\frac{r}{R}\right)^3 \sqrt{1-\left(\frac{r}{R}\right)^2}$$

and is also shown in Fig. 2. The mathematical analysis of the flow through a rotor with this load distribution over the disc has been carried through by W. Mangler and the computations by P. Sibbald, and a detailed report on this work will be issued in due course. We proceed to consider some of the results, beginning with the induced velocity distribution over the disc itself.

The contours of induced velocity normal to the disc, denoted by v, for the above loading and taking $C_T = 1.0$ are given in Figs. 3 and 4 for disc incidences (i) of 0 and 15°. Calculations have also been made for 30, 45 and 90 degrees.

If we consider in particular Fig. 4 (i = 15°) we notice first that the induced velocity is anything but uniform over the disc. The average value of the downwash parameter $\frac{v}{VC_T}$ is about 0·25 but it varies from an upwash



INDUCED VELOCITY OVER DISC
CONTOURS OF $\frac{v}{VC_T}$ FOR $\alpha = 0°$

Fig. 3.

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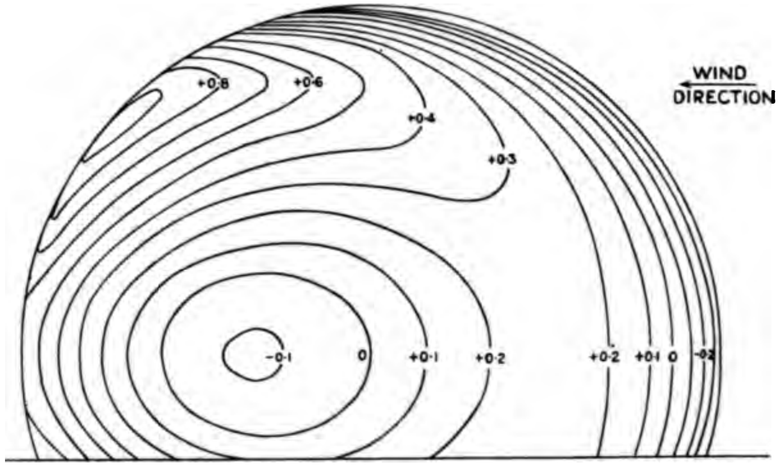
of 0·3 at the front of the disc to a downwash of 0·9 on the rear edge of the disc halfway out along the span. It is desirable here to mention another feature which is characteristic of this kind of investigation and which is already well known in aerofoil theory: this feature is that the induced velocity varies rapidly with any change in the load distribution over the disc. This



INDUCED VELOCITY OVER DISC
CONTOURS OF $\frac{v}{VC_T}$ FOR $\alpha = 15°$

Fig. 4. *Crown copyright reserved.*

is because the induced velocity depends on the gradient of the loading and it follows that large local changes in induced velocity can be obtained by quite small changes in the load distribution on the disc. Consequently local peaks in upwash or downwash may not be present in practice because they can be removed by quite small changes in loading; we must therefore only take the general features as significant. These general features are best considered in relation to the vortex system shown in Fig. 5 which represents the system roughly.

In Fig. 5 the number of arrows shown is a measure of the vortex strength. It must be remembered of course that we are actually dealing with a continuous variation of vorticity, and the diagram only illustrates the main features. We note the following:

(1) There is an upwash near A at the forward part of the disc.
(2) There is a downwash along BO which is followed by upwash over OC and downwash over CD. These are all in accordance with the detailed calculations.
(3) There is zero downwash at the centre of the disc.
(4) There is a large upwash at the lateral tips of the disc EE and a large downwash near the points FF; as explained above these may be modified by minor changes in load distribution.

On the right of Fig. 5 is shown the span loading distribution which is obtained for the disc loading given by equation (2), treating the rotor as an aerofoil. It will be seen that this loading distribution differs considerably

from the ideal elliptic loading which gives minimum induced drag for aerofoils.

We now turn from the case of the induced velocity in the rotor disc to the case of the induced velocity away from the disc. Since we are here mainly interested in the mean value with respect to time of the induced

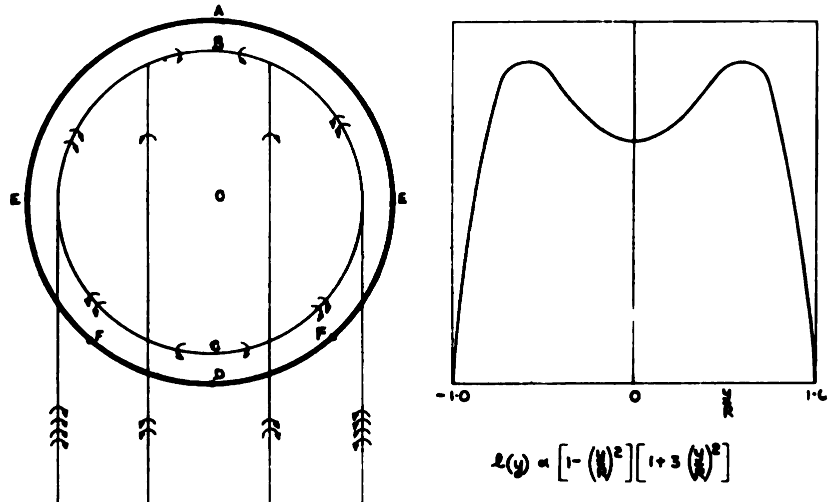


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Fig. 5. Vortex Distribution and Span Loading.

velocity at a point we can here satisfactorily represent the rotor as a disc with a steady load distribution over it. The same loading as in the former case has been adopted, given by (2), and the calculation of the induced velocity distribution has been made by the same method as for points on the disc. Here we are of course interested in induced velocities normal to the wind direction since the results are to be applied to calculate interference effects. Figs. 6 and 7 show the downwash $\frac{w}{VC_T}$ in the plane far downstream for a rotor at zero incidence and at an incidence of 15°. The plane of the figures is normal to the stream direction so that in Fig. 6 the projection of the rotor disc is shown as a line and in Fig. 7 as an ellipse, and w is the induced velocity directed vertically downwards in this plane.

These curves can be applied to a number of important problems in helicopters. Consider first the interference effect on induced drag for a pair of rotors. If the rotors are side by side each will produce an upwash on the other and a reduction of the induced drag will result. If on the other hand, there is one rotor behind the other the front rotor will produce a downwash on the rear one with a consequent increase in induced drag. These effects are of course well known in wing theory. We obtain the results given in Table I for the side-by-side configuration.

Table I.

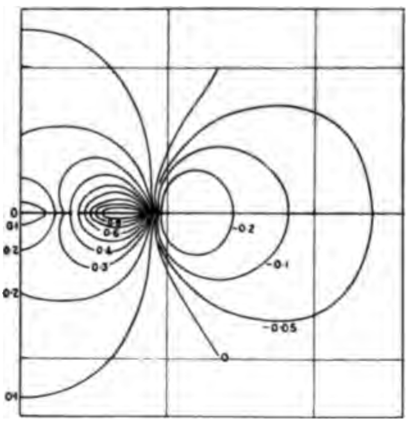
INDUCED DRAG OF SIDE-BY-SIDE ROTOR COMBINATION.

DISC INCIDENCE ZERO.

$\dfrac{\text{Horizontal Gap}}{\text{Diameter}}$	$\dfrac{\text{Induced drag}}{\text{Induced drag without interference}}$
0	0·875
0·05	0·906
0·1	0·924

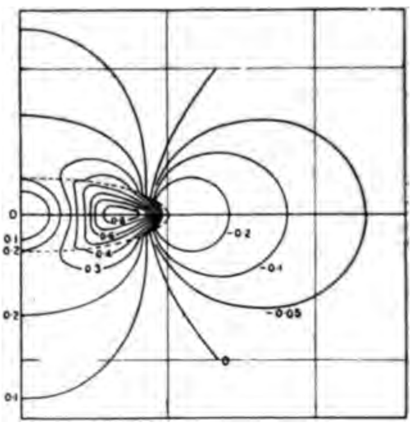
The induced drag of an isolated rotor at zero incidence with the disc loading distribution shown in Fig. 2, where the span loading distribution is as shown in Fig. 6, is calculated to be 1·1·76 times the induced drag for the ideal case of elliptic loading across the span; this result has been used in the calculation of induced drag for a combination.

For gap-diameter ratios of less than 0·1 the favourable effect may be rather greater than that shown because the effective disc loading may possibly change in such a way that the two discs act more and more like a single disc.



INDUCED VELOCITY FAR DOWNSTREAM CONTOURS OF $\frac{w}{VC_T}$ FOR $\alpha = 0°$.

Fig. 6.



INDUCED VELOCITY FAR DOWNSTREAM CONTOURS OF $\frac{w}{VC_T}$ FOR $\alpha = 15°$

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Fig. 7.

It is clearly desirable to place the discs as close together as possible without increasing the induced drag, since this reduces the length of the ourriggers. I don't know the answer to this problem but my guess is that the best arrangement would be to use a small overlap on the discs; this would not normally give any risk of the blades striking one another since the rotors are usually geared together.

The next important case of induced drag is for the helicopter with tandem rotors. Here in the extreme case of no gap between the rotors the

$\dfrac{\text{Vertical Gap}}{\text{Diameter}}$	$\dfrac{\text{Induced drag}}{\text{Induced drag without interference}}$
0	2
0·1	1·573
0·2	1·394
0·35	1·259
0·5	1·182

TABLE II.

INDUCED DRAG OF TANDEM ROTORS

DISC INCIDENCE ZERO.

induced drag may be twice as great as the drag of the two independent rotors. The results for different vertical gaps between the rotors are given in Table II and it will be seen that the interference effect diminishes rapidly with increase in gap. This interference effect is independent of the fore and aft distance between the rotors but the gap should really be estimated as the distance of the wake of the front rotor from the rear one ; due to the deflection of the wake this may be somewhat greater than the geometrical gap.

ROTOR INTERFERENCE FOR MULTI-ROTOR HELICOPTERS.

In order to analyse or predict the stability characteristics of multi-rotor helicopters it is necessary to estimate the interference between the rotors. This requires the calculation of the downwash induced by the front rotor(s) on the rear rotor(s). The other interference effects are not likely to be important with the possible exception of the effect of the rotor slipstream on the fuselage at low forward speeds.

A description of calculations of the induced velocity field of a rotor has been given above and it is only necessary to indicate briefly the application to the calculation of stability here. For the tandem rotor helicopter the rear rotor is in a stream which is inclined downwards due to the downwash from the front rotor and this would cause a reduction in thrust if it were not counterbalanced by a change in pitch of the blades or a change in inclination of the rotor axis. This downwash varies with forward speed and with the height of the rear rotor above the front one, so that it is not possible to draw many general conclusions as to the effect on stability of the rotor interference. Since the effect increases with reduction of forward speed but vanishes altogether in the hovering condition, to which the theory does not apply, there will be some speed for which the effect is a maximum.

As the speed decreases the slipstream of the front rotor is deflected more and more from the wind direction and consequently further and further away from the rear rotor. Since our theory is a first order theory which assumes that the loading of the rotor and the deflection of the slipstream are both small the theory becomes less reliable as the speed decreases. It may, however, be possible to make some allowance for second order effects by estimating the height of the rear rotor above the deflected slipstream of the front rotor.

Stability.

SINGLE ROTOR AIRCRAFT.

(*a*) *Hovering.*

The helicopter is least like an aeroplane when it is hovering and it is in this condition that we should expect that the stability characteristics would be most unusual. This is in accordance with experience which shows that the hovering helicopter in its simple forms is unstable : this instability takes the form of an increasing oscillation. It is desirable to be clear about this and not to be confused by meaningless statements about " pendular stability."

It has been often forgotten that Von Karman gave an adequate account[3] of the stability of the hovering helicopter in 1921. His work had been done in connection with the Karman-Petroczy helicopter developed in Austria-Hungary during the 1914-1918 war. I repeated this investigation in 1938 in an unpublished paper[4] in ignorance of Von Karman's work, and in the same year Hohenemser[5] published a much more detailed investigation of the subject.* Fortunately this instability of the hovering helicopter turns out to be of long period and fairly slow rate of growth. For example, for the Sikorsky R.4 the period of oscillation is 14 sec. and the increase in amplitude in one period is about 5.

(*b*) *Forward flight.*

In forward flight we should logically begin by considering static longitudinal stability which is measured by the variation of the position of the fore-and-aft control with forward speed. It appears, however, that this movement is small and independent of C.G. position so that we should conclude that the static longitudinal stability of the aircraft is neutral or that the concept is inapplicable.

I shall not discuss the dynamic stability here as work on this will be described by Mr. Stewart in a lecture to the R.Ae.Soc. in January, 1948.

Helicopter Stability—General.

The single rotor helicopter of the Sikorsky type is an aircraft whose stability characteristics are very different from the stability characteristics of aeroplanes : the small effect of C.G. position on the stability of the Hoverfly I helicopters is sufficient evidence of this. Helicopters with two side-by-side rotors behave like single rotor helicopters for motion in the plane of symmetry.

But when the lifting surfaces are spread out along the line of flight, as in tandem rotor helicopters, then the resemblance, from the stability point of view, to aeroplanes becomes closer. In the following paragraphs I shall for definiteness refer to the tandem rotor helicopter but it must be understood that the remarks apply in general to other configurations, such as the Cierva Air Horse, which has three rotors at the corner of an equilateral triangle.

In considering the general problems of the stability of the multi-rotor helicopter we must take advantage of the many years of study devoted to aircraft stability. We follow here the theory of Gates and Lyon[8]. These

* The corresponding theory of rotor stability in forward flight has been worked out by Hohenemser[6] and Sissingh[7]

writers have shown that the principal parameters determining aircraft stability are the static margin K_n and the manoeuvre margin H_m and that for satisfactory behaviour it is necessary that both these quantities should be positive.

The definitions of K_n and H_m are* :—

(1) $$K_n = -\frac{\delta C_m}{\delta_\alpha}\frac{d\alpha}{dC_L} - \frac{\delta C_m}{\delta V}\frac{dV}{dC_L},$$

with $$\frac{dV}{dC_L} = -\frac{V}{2C_L},$$

(2) $$H_m = -\frac{\delta C_m}{\delta_\alpha}\frac{d\alpha}{dC_L} - \frac{\delta C_m}{\delta_q}\frac{dq}{dC_L},$$

with $$\frac{dq}{dC_L} = \frac{V}{l}\cdot\frac{1}{2\mu_1},$$

where α = incidence.

C_L = lift coefficient $2L/\rho V^2 S$.

C_m = pitching moment coefficient $2M/\rho V^2 Sl$.

l = arm for pitching moments.

q = angular velocity in pitch in a circle at constant speed.

μ_1 = $W/g\rho Sl$.

The neutral point is the C.G. position for which K_n vanishes and in the simplest cases K_n is proportional to the distance of the C.G. ahead of the neutral point. Further the static margin K_n is proportional to the rate of movement of the longitudinal control with speed, and the latter vanishes if the C.G. is at the neutral point. This relation between K_n and the longitudinal control provides a good way of understanding the significance of the static margin. We consider the succession of equilibrium conditions of the aircraft which corresponds to increases in speed at constant power. Then there will be a corresponding movement of the longitudinal control lever which may be assumed to tilt the rear rotor forward and back just as if we had a gigantic all-moving tail plane ; if this movement is such that the backward tilt of the rear rotor increases relative to that of the front rotor with increase of speed (corresponding to downward movement of the elevator with increase of speed for a stable aeroplane) then the helicopter is statically stable.

The neutral point and the static margin are linked with slowly developing changes in motion and do not give the whole picture. An aircraft which is statically unstable may be quite controllable ; nevertheless it is desirable that helicopters which are to be used for military or civil purposes should be

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* Ignoring the distinction between the lift coefficient C_L and the resultant force coefficient C_R.

statically stable for speeds above some lower limit ; this lower limit might be the best climbing speed.

On the other hand the manoeuvre margin H_m is a measure of the effects of rapid changes and it is essential that H_m should be positive. If H_m is negative large accelerations can be developed as a result of small movement of the longitudinal control lever and this is unacceptable.

For the tandem rotor helicopter we can carry our analysis a little further. If the aircraft is given a rate of pitch q then the front rotor hub will acquire an upwards velocity and the rear rotor hub a downwards velocity (Fig. 8).

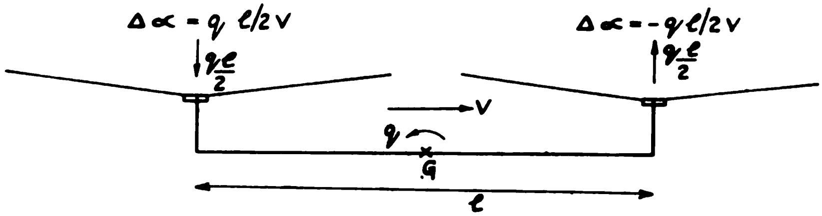

Fig. 8. *Crown copyright reserved.*

This will produce a decrease in thrust of the front rotor and an increase of thrust of the rear rotor and hence a negative pitching moment. For the twin rotor helicopter rough estimation gives

$$\Delta M = \frac{1}{2}\frac{dL}{d\alpha}\Delta\alpha = -\frac{l^2 q}{4V}\frac{dL}{d\alpha}$$

and hence
$$\frac{\delta C_m}{\delta q} = -\frac{1}{4V}\frac{dC_L}{d\alpha},$$

where $\frac{dC_L}{d\alpha}$ is the overall variation for both rotors. Substitution in the equation defining H_m then gives

$$H_m = -\frac{\delta C_m}{\delta\alpha}\frac{d\alpha}{dC_L} + \frac{1}{8\mu_1}\frac{dC_L}{d\alpha}.$$

Now μ_1 is of order unity and $\frac{dC_L}{d\alpha}$ is of order unity for a tip speed ratio $\mu = 0{\cdot}1$ and of order $0{\cdot}4$ for a tip speed ratio $\mu = 0{\cdot}3$. Hence the second term in the right hand side of the expression for H_m is of order $0{\cdot}1$ for $\mu = 0{\cdot}1$ and falls with increase of tip speed ratio. This rough calculation is sufficient to show that the second term in the expression for H_m is important, probably more important than for aeroplanes. We must therefore be on our guard against the simple criterion that satisfactory stability characteristics are assured if $\frac{\delta C_m}{\delta\alpha}$ is negative, as this is not the whole story.

As an example, calculations have been made of the stability characteristics

at sea level of a hypothetical tandem rotor helicopter of the following dimensions :—

Weight	9,500 lb.	Solidity	0·05
Rotor power ..	2 × 350 h.p.	Tip speed	550 ft./sec.
Rotor diameter ..	45 ft.	Distance between rotor hubs l=	45 ft.

The results are given in Fig. 9 which shows static margin, manoeuvre margin and longitudinal control setting plotted against the tip speed ratio μ for two c.g. positions, one midway between the rotors and another forward of it by 5 per cent. of the length between the hubs. It will be seen that the manoeuvre margin is positive in all cases and this suggests that there is no risk of rapid divergence. On the other hand with the rear c.g. position the static margin is negative throughout the speed range. With forward c.g. we have static stability at high speeds and static instability at low speeds. It seems likely that static instability may occur for all tandem rotor helicopters below a certain speed and it may be only practicable to require that this speed shall be below the best climbing speed.

The longitudinal control setting is defined as the angle of tilt of the rear rotor axis relative to the front rotor axis, a backward tilt being positive. If we wish to travel faster the immediate movement is to increase this angle

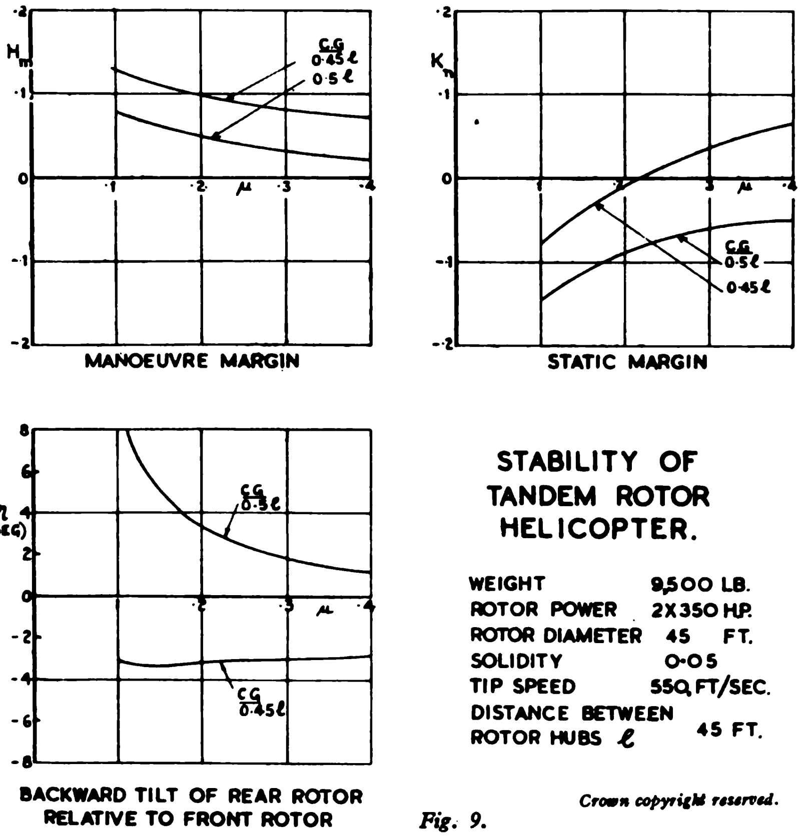

Fig. 9.

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as it will give greater lift on the rear rotor and this will tilt the nose down. It is very desirable that such a movement should not have to be followed by too much reversed movement when we reach the new condition. This happens for a statically unstable aircraft as is shown for the helicopter with rear c.g. position in Fig. 9. With the forward c.g. position on the other hand the longitudinal trimmer setting hardly varies at all with speed which is much more satisfactory.

I am not sure how far it is safe to generalise from this one example which was calculated in rather a hurry. In particular, the effect of drag and of vertical height of the c.g. have been neglected. But it is probably correct to conclude that the maintenance of static stability over a sufficient part of the speed range is the matter to which most attention should be given.

CONCLUDING REMARKS.

I have left a number of matters not properly illustrated by means of examples. There has been no opportunity so far to do much of this but we shall try to do some more in the future. I will conclude my lecture by expressing the hope that perhaps some members of the audience may be willing and able to take some part in this work.

THE CHAIRMAN'S VOTE OF THANKS TO MR. SQUIRE.

The CHAIRMAN said he had very much pleasure in proposing a hearty vote of thanks to Mr. Squire for his most interesting lecture, and felt all present were well rewarded for coming there that afternoon.

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Third Annual General Meeting

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24TH APRIL, 1948.

CHAIRMAN'S SPEECH.

ADIES AND GENTLEMEN,

At this, the Third General Meeting and the Second Annual General ieeting of the Helicopter Association, it is my privilege to present to you this address some information which I hope will be of interest.

General Remarks—Membership. Firstly, I am happy to say that the embership of the Association continues steadily to increase. Although is means an increased income, the actual running expenses of the Associa- on have increased even more, there are however, two ways of meeting the tra load placed upon the Association's funds. The first and obvious ing for your Council to recommend would be an increase in the annual bscription and although we may be forced to place before you within the ext few months a proposition to this effect, we are anxious to defer the atter as long as we can conveniently do so. The second—and to my mind e better way of easing the burden, would be to aim for a still greater increase membership between today and our next General Meeting in 1949, and I am hoping that each and every member will take it upon himself to cruit at least one new member during the coming year, remembering that e new members must be persons who carry the clear qualifications set out the Rules and Regulations of the Association. More especially we wish encourage the recruitment of the younger entrants, for with the industry panding as it is every encouragement and aid must be given to those who ily now have their feet upon the first rung of the ladder. Our aim should to double our membership and this can only be accomplished if every ember will do as I have suggested.

Finance. On the subject of finance you will have seen from the printed nnual Report that although our financial position is sound, our reserves e slender. The sound position today is due mainly to the generous sponse from the industry to the appeal for funds. The funds received in

the form of Foundation Grants total more than £1,000, and the Council wishes to record its appreciation of the action of the Directors of the Bristol Aeroplane Co., Ltd., The Cierva Autogiro Co., Ltd., The Fairey Aviation Co., Ltd., and Westland Aircraft Ltd., who have each generously donated the sum of £250. These sums have been placed to a Special Reserve Fund, but it has been necessary to transfer £400 from that account to the Income and Expenditure Account for the year to February, 1948.

Journal. I will now refer to the Journal of the Association. The high quality of the matter delivered by the lecturers during the year demanded an improvement in the method of presentation over that provided by the earlier publication known as the Bulletin, and the Council feel that their action in improving the form of the Journal has been fully justified, although there has been an unavoidable increase in the cost of printing and publishing. It is interesting to note that the Journal is now circulated throughout the principal Government Departments, many Universities and other scientific and educational institutions throughout the world. The heavy burden of the expense of printing and publication has to some extent been eased by the token advertisement scheme to which the industry has given very satisfactory support. New applications for space continue to come to hand together with applications to subscribe from manufacturing concerns throughout the aircraft industry.

Cierva Memorial Prize Essay. It will be remembered that an anonymous donor has given a prize of £100 for a paper or papers to be written on any subject connected with helicopters, and with the consent of the donor this sum forms the nucleus of the Cierva Prize Essay Fund. The standard of entries for this competition for the year 1946/47 were disappointingly low and, therefore, the Committee dealing with this matter recommended that the award be withheld for that year and this decision was endorsed by your Council.

Your Council has considered a change of subject for this essay for the ensuing year and suggestions from members will be welcomed. An announcement will be made as soon as a decision has been reached. The *entry* for the session 1947/48 is now under consideration. You will note that I deliberately said entry, and the Council do hope that a better response will be forthcoming for this year.

Lectures. I will now turn to the subject of lectures. During the year seven papers have been delivered to the membership by such well known helicopter engineers as Messrs. IGOR SIKORSKY, H. B. SQUIRE, J. S. SHAPIRO, R. HAFNER, O. FITZWILLIAMS, A. MCCLEMENTS and Major SILTANEN, U.S.A.A.F. Each lecture has been followed by an informal discussion, and refreshments and every opportunity for getting together and discussing the various helicopter developments and events has been taken by members.

Emblem. A great deal of thought and careful consideration has been given to the problem of a suitable emblem for the Association and finally your Council has selected the Dragonfly as the most suitable object in nature having as it does all the flying characteristics of the helicopter. The Emblem Committee headed by Major NELSON has devoted much time and labour to the preparation of sketches and designs, and the result is the badge which you will shortly see reproduced in black and white on the cover of the Journal and other documents. It will be used for an experimental period of twelve months and members are invited to submit their criticisms.

Annual Dinner. The success of our first Dinner in March, 1947, suggested that it should be made an Annual event. As you know, it is being held this year in Londonderry House which is rapidly becoming a centre of aviation activities, and I should like to record our thanks to the Secretary General and House Secretary of the Royal Aero Club for the use of their excellent premises and the kindly advice given in organising this function.

Rules and Regulations. On the subject of the Association Rules and Regulations, I think you will agree that certain aspects require clarifying and generally straightening out. Membership qualifications in particular call for revision in the light of experience and in due course your Council will place the proposals before you in detail.

Council. I should like to take this opportunity of extending a warm welcome to the newly elected Members of Council and to those who were not successful I would say, do not be disappointed, and better luck next time.

The absence of four of our Council Members is to be regretted, but at the same time they are much to be envied. Captain LIPTROT, Dr. BENNETT and Messrs. HAFNER and FITZWILLIAMS are on a visit to the U.S.A., and taking part in the Fourth Annual Forum of the American Helicopter Society which is just about to close. No doubt they will return with much information about recent developments in America.

Staff. As you will have seen from the report, the Council has appointed Miss SHEILA MACPHEE as Assistant Secretary. Miss MACPHEE has approached her work with great enthusiasm, and I know that should any member be in need of advice and information on Association matters it will readily be provided by her.

Liaison with Official Bodies Your Association now enjoys full recognition by the Ministry of Civil Aviation and Ministry of Supply, and is represented on numerous Committees and Working Groups dealing with the Regulatory aspects of helicopters and the conditions of issue for Helicopter Pilots Licences and Instructors Certificates, Certificates of Airworthiness and Landing Area Requirements. The appointed members are collaborating closely with such important bodies as the Royal Aeronautical Society, the Air Registration Board, the Society of Licensed Aircraft Engineers, the Guild of Air Pilots and the Royal Aero Club.

Outstanding Events, 1947/48. The year under review will be memorable in many ways. In June, 1947, the Westland Aircraft Company announced their intention to manufacture the Westland Sikorski S.51 in this country. Two British helicopters, the Bristol 171 and the Fairey "Gyrodyne," commenced their initial handling and prototype trials and great progress is being made in the development of both these types.

On the operational side British European Airways have successfully established the experimental postal delivery unit, and the mail carrying will shortly start in earnest. In Scotland the Irvin-Bell organisation has inaugurated the first civil Helicopter Training School, and at Cambridge the Pest Control Company is carrying out experiments in crop-spraying by helicopter on a large scale.

A notable demonstration took place for the Elder Brethren of Trinity House at Dungeness, Kent. The demonstration was designed to prove the suitability of the helicopter for coastal rescue and relief work, and early this year the opportunity came for a full scale demonstration under the

worst possible flying conditions when Trinity House requested that aid by way of provisions and stores be delivered to the men of the Wolf Rock Lighthouse, which operation was successfully accomplished by the Westland S.51 helicopter.

Landings have been made in the London Area by the Westland S.51, and a Bell helicopter. The pilots of both these aircraft are members of the Association, and from members point of view probably the most interesting landing was that made within 50 yards of this building on a small space adjoining Broadcasting House.

CONCLUSION.

Finally, I should like to commend and express appreciation to all those Council and other members who have given so unstintingly of their time and labours to the furtherance of the Association's work and aims. Particular mention should be made of our Vice-Chairman, Mr. NORMAN HILL, and the Honorary Secretary, Mr. STOKER, who between them have been responsible for the major part of the day to day work of the Association during the past year.

Our thanks are also due to the Secretary of the Society of Licensed Aircraft Engineers for his real help and advice, and last but not least to the firm of Messrs. W. B. KEEN & Co., who have acted as the Association's auditors and accountants during the past year and supplied other services as well.

Election of Chairman

At the First Meeting of the newly-elected Council of The Helicopter Association of Great Britain on 20th May, 1948, MR. H. A. MARSH, A.F.C., A.F.R.Ae.S., was unanimously re-elected Chairman for the ensuing year.

MR. N. J. G. HILL, A.M.I.Mech.E., A.R.Ae.S., Vice-Chairman for 1947 was also unanimously re-elected for 1948.

The Second Annual Dinner

Chairman: H. A. MARSH, ESQ., A.F.C., A.F.R.Ae.S.

After the Annual General Meeting on April 24th, Members and their friends gathered in the evening to celebrate the Second Anniversary of our Association. In order to accommodate the rather larger assembly of just over a hundred people, the dinner was held at Londonderry House, Park Lane. The dignity of the Banqueting Hall, by comparison with last year's smaller gathering in the City, blended well with the informal and friendly atmosphere of the occasion.

Following the CHAIRMAN's speech, Mr. PERCY CARPENTER responded to the toast "The Guests" proposed by Wing Commander REGGIE BRIE and Captain LAURENCE PRITCHARD, and Captain LAURENCE PRITCHARD's comments on the economics of Aviation were particularly apt and amusing to Members, especially when recalling the witty vein of his speech at our first Dinner. Other speakers were Mr. S. SCOTT-HALL and Mr. N. E. ROWE, who jointly proposed the toast of the "Helicopter Association" with some flattering remarks about the enthusiasm of its Members. The evening was concluded by our VICE-CHAIRMAN proposing a toast to "The Ladies."

Among the Association's official guests present were, Captain J. Laurence Pritchard, Mr. R. E. Hardingham, Colonel R. L. Preston, Mr. I. L. S. McNicol, Mr. P. Carpenter and Major M. E. A. Wright, and, of the technical press, Mr. C. M. Poulsen, Mr. Thurstan James, Mr. W. E. Goff, Mr. J. Parke and Mr. C. F. Andrews.

Proceedings of the Third Annual General Meeting

HELD AT

MANSON HOUSE, 26 PORTLAND PLACE, LONDON, W.1

ON 24TH APRIL, 1948

At 3 p.m., the Notice convening the Meeting was read by the Honorary Secretary ; apologies for absence were received from the following Council Members, Group-Captain R. N. LIPTROT, Dr. J. A. J. BENNETT, Mr. R. HAFNER and Mr. O. FITZWILLIAMS, who were attending the Fourth Annual Forum of our counterpart, the American Helicopter Society.

Our Chairman then read a cable he had sent on behalf of Members :—

" RICHARD PREWITT, President of American Helicopter Society. Heartiest greetings from the Helicopter Association of Great Britain to the American Helicopter Society on the occasion of their Fourth Annual Forum. H. A. MARSH, Chairman."

Unfortunately, the following reply arrived too late to be read at the Meeting :—

" The CHAIRMAN, Helicopter Association of Great Britain, Greetings and congratulations on Third Annual Meeting and Dinner from American Helicopter Society. RALPH LIGHTFOOT, President."

The Minutes of the Association Second Annual General Meeting held on March 22nd, 1947, were read by the Honorary Secretary, Mr. J. S. SHAPIRO proposed that these Minutes be approved and Mr. G. A. FORD seconded the proposal, which was passed unanimously.

Our Chairman presented this year's Annual Report which was read to Members by the Vice-Chairman. The accounts were presented by the Hon. Treasurer, Mr. G. C. TURNER and after some discussion, the Report and Accounts for the year ended 29th February, 1948, were accepted.

The result of the Ballot for vacancies on the Executive Council was announced and, on the proposal of Dr. A. P. THURSTON, seconded by Mr. A. E. BRISTOW and subsequently carried unanimously, the following successful nominees were elected to the Executive Council :—H. A. MARSH, B. H. ARKELL, N. J. G. HILL, A. MCCLEMENTS and Major H. O. NELSON.

Messrs. W. B. KEEN & Co. were reappointed the Association's Auditors for the coming year.

The Chairman, after making his speech, which we have reported fully elsewhere, intimated that the Council would welcome suggestions from Members regarding the preparation of a suitable lecture programme for the coming year and for ideas concerning ways and means of increasing the Association's funds. In his concluding remarks, he said he took pleasure in pointing out that over 50 per cent. of the Association's Members had recorded their votes and he understood that this was a very high average compared with contemporary Associations and Societies.

Other matters discussed included a proposition for charging Members a small amount for the Journal, the possibility of the Association's publishing or sponsoring the publication of a text book on helicopters, the increase of revenue through advertisements in the Journal, the closer relationship with the Press and the possibility of organising a helicopter display.

The Meeting closed at 4.30 p.m.

EIGHTH LECTURE

A Description of the Bristol Type 171, Mk. I

By RAOUL HAFNER

A lecture presented to The Helicopter Association of Great Britain on Saturday, 28th February, 1948, at Manson House, 26 Portland Place, London, W.1.

H. A. MARSH, A.F.C., A.F.R.Ae.S., IN THE CHAIR

INTRODUCTION BY THE CHAIRMAN.

LADIES AND GENTLEMEN,

Our lecturer today is too well known to all of you to need any introduction from me. MR. HAFNER is a member of the Council of our Association, a member of the Helicopter Committee of the Aeronautical Research Council and Chief Designer, Helicopter Division, of the Bristol Aeroplane Co. Ltd.

Since he talked to a joint meeting of the S.L.A.E. and our Association in April, 1946, the Bristol Helicopter 171 has successfully flown and is now accumulating flying time at a rapid pace. I am sure we shall all watch the progress of the 171 with very great interest, particularly as it would appear to have possibilities of being the first British helicopter to go into production.

On behalf of the Association I extend a cordial welcome to all our guests.

MR. RAOUL HAFNER.

MR. CHAIRMAN, LADIES AND GENTLEMEN,

It is my task this afternoon to give you the story of a British helicopter, about which you have probably already heard, the Bristol Type 171.

It is a story of a sustained effort and one is reminded of a mountaineering expedition which commences as a very comfortable walk on gentle slopes but is gradually getting into steeper and more stony territory until eventually one finds oneself clinging to a nearly vertical wall, exhausted, frightened and short of breath, and when from this position the mountaineer casts his eyes back to the starting point, he is forcefully reminded of the fact that everything looks rather higher and more difficult from above than it seemed from below, even though the difficulties were not unexpected ones.

My story begins in the late Autumn of 1944 when I joined the Bristol Aeroplane Company, with the mandate to form a Helicopter Department and to produce, within the shortest possible time, a practical helicopter which could earn its living and be sold to a customer. The experience then with helicopters in this country was very limited. We had some Sikorsky Y.R.4's flying around, there were a handful of pilots, and very few people with technical training on helicopters. There was a complete lack of research equipment suitable for this kind of work and Air Marshal SORLEY, then C.R.D., stressed the necessity for an early practical solution of the problem which eliminated at the outset any advanced design that would have involved us in long term basic research. I therefore decided to confine our efforts to well tried elements, which resulted in the choice of the following features of the Type 171 ;

(*a*) The Sikorsky Y.R.4 pattern as the basic configuration of the helicopter, *i.e.* a main rotor with cyclic and collective pitch control, and a torque compensating tail rotor providing yawing control.

(*b*) The main rotor control, hub, and blade suspension to follow the lines of that in the Hafner Gyroplane.

(*c*) A wooden monocoque construction for the rotor blades. with which we had gained some experience in this country during the war, and,

(*d*) The fuselage, or at least the greater part of it, built in metal monocoque construction, in accordance with well tried Bristol practice.

With regard to the size of the aircraft, it was already then recognised that the useful load of the Y.R.4 was too small to be economical, but that, on the other hand, it would be dangerous, at that stage to venture too far into the larger rotor sizes, as scale effect would bring many yet unknown problems into the picture.

A rotor of not more than 50 feet diameter and an all up weight of between 4,000 to 5,000 lb. was thought to be a fair compromise. An improvement in helicopter performance, especially speed, has always been one of my aims —as well as simplicity and robustness of construction and good wearing properties—which would result in low maintenance cost and a long service life.

In the New Year 1945, the nucleus of the helicopter section was established and the deck was cleared for action—a helicopter design suitable for production. We had a formidable task before us, which required a carefully thought out plan. Before proceeding on this task we had to build the tools to make the job. In the first instance there were a number of aerodynamic problems which could not be solved without full scale investigation on a rotor spinning tower : we therefore designed and constructed the Bristol Rotor Tower. Next the need for fatigue testing of components, which are subject to wear, became apparent, in particular blade articulations like flapping and drag hinges and tie rods : such a testing machine was designed and constructed.

A theoretical analysis of rotor oscillations in the plane of rotation resulted in the construction of a dynamic model rotor, which is still unfinished, and many other minor items of research equipment, the description of which would go beyond the scope of this simple account.

Our next serious handicap was the lack of airworthiness and strength requirements for this type of aircraft. AP.970 and the corresponding A.R.B. requirements were mostly inapplicable to the helicopter, so that we decided to write such a document ourselves. At the commencement the progress on such unprepared ground was slow and trying, but gradually we gathered momentum and once the principal questions were settled the design work could fan out and advance in many directions. Drawings were issued to the work-shops, and slowly components and sub-assemblies began to collect in the Works Stores, ready for the major assembly of the aircraft. Steadily this grew until, on the 17th January, 1947, the Bristol 171 was wheeled out into the open air where Works people gathered around it and gazed upon this queer contrivance, with expressions which clearly revealed mixed feelings on the subject.

This ceremony concluded the first and somewhat simpler part of our journey. The assembly of the aircraft had proceeded satisfactorily, and indeed many of the vital components had already been subjected to a considerable measure of fatigue and other testing, but the main assemblies as whole units had not yet been put to a test. Consequently, the rotor and hub were removed from the aircraft and assembled for the first time on the rotor tower, where they spent the following four months. During this time a series of tests were carried out which involved in all some 70 hours running. Meanwhile a large brake fan was attached to the aircraft, in lieu of the rotor, and this assembly was ground tested for a period of some 30 hours. The purpose of these tests was to establish the suitability of all mechanical parts, to gain experience on the working condition of the engine, on vibration levels, and other features. After these tests the rotor and the aircraft in all its essential parts was dismantled, thoroughly inspected and re-assembled for flight trials. The first ground running of the helicopter with the real rotor was carried out on 9th May, 1947. It was then found that the control forces and vibrations due to manufacturing inaccuracies in the blades were excessive, and tabs were fitted to the blades in order to correct these errors. These and other modifications gradually improved the rotor control sufficiently to permit an increase of rotor speed to the higher speed range.

Then a new problem arose. On 20th June, 1947, during a ground running test, a new kind of vibration was experienced, commencing as a slight vertical vibration of the fuselage. It built up, within a very short space of time, to violent proportions with visible flapping movements of the blades. This was found to be rotor blade flutter. The rotor was taken back to the spinning tower and showed here too flutter signs at unexpectedly low speeds. We made investigations and found that, as a result of small modifications carried out on the blade, since it had been last on the tower, its C.G. was slightly moved aft of the aerodynamic centre, which caused this pronounced reduction in critical flutter speed. Preponderance weights were then fitted to the blade, which brought the critical flutter speed outside the operational speed range. During the following period further refinements were made to the rotor controls until, on 27th July, 1947, the test pilot reported that the aircraft was ready for a test flight. That day it became airborne for the first time, and after a number of familiarisation flights on the same evening, Mr. H. A. Marsh had gained sufficient confidence to give a number of people short " joy-rides " and had logged 30 minutes flying time

that day. Thus the second important milestone on our journey was successfully passed.

The following development was slow and not very spectacular. Five hours were made mostly in hovering and slow flight, but we gained experience in the control of the aircraft. Many forms of control dampers were tried out with varying results, until eventually we decided to use an inertia damper in the azimuth control, and a friction damper in the collective pitch control, which, together with further balancing of the rotor blades, reduced the control forces to quite negligible proportions. The next few hours were spent in more ambitious flying including quicker manoeuvres and an increase in speed.

The aircraft was then due for another breakdown and inspection, which showed that the wearing parts were in very sound condition. As a result the previous flight restrictions were removed and the aircraft was now officially cleared for flight at any speed and height. This enabled us to extend the flight envelope considerably, and to date the following flight tests have been completed :

Straight level flights up to a speed of 110 m.p.h.
Climb at full load up to 6,000 feet.
Handling and flying under gusty conditions in winds up to 50 m.p.h.
Hovering at various heights and
Auto-rotative glides at full load from 6,000 feet.

In all, the first prototype aircraft has carried out some 30 hours ground running followed by 40 hours flying, and a second prototype aircraft, after extended ground testing, has taken the air recently.

After this brief account of the technical development of the Bristol 171, I shall proceed to give you a description of this aircraft.

MAIN ROTOR.

(a) Rotor Blades.

The three rotor blades are of straight taper in plan form, and a slight reflex section gives a stable centre of pressure. The chord thickness ratio is 7% at the blade tip and 13% at the blade root. The thin section at the blade tip is necessary to avoid shock stall at high mach numbers.

The blade is carefully mass balanced at all stations in order to avoid pitching moments in flight which would be transmitted to the flying controls and to avoid blade flutter which is likely to arise if the C.G. of the section lies aft of its aerodynamic centre. Tabs are provided to correct any manufacturing errors and reduce the moment co-efficient C_{Mo} to zero.

The blades are of wood and a monocoque form of construction is employed. There is a solid laminated spar extending from the L.E. to approximately 1/3 of the chord and the rear portion is made up of spruce ribs and trailing edge covered by a plywood skin. The longitudinal mass distribution of the blade is such that bending moments in flight are reduced to a minimum. This necessitates a light construction at the blade root, becoming heavier towards the blade rip, and this form of mass distribution has been achieved by inserting lead weights between the laminations in the solid part of the blade at suitable intervals.

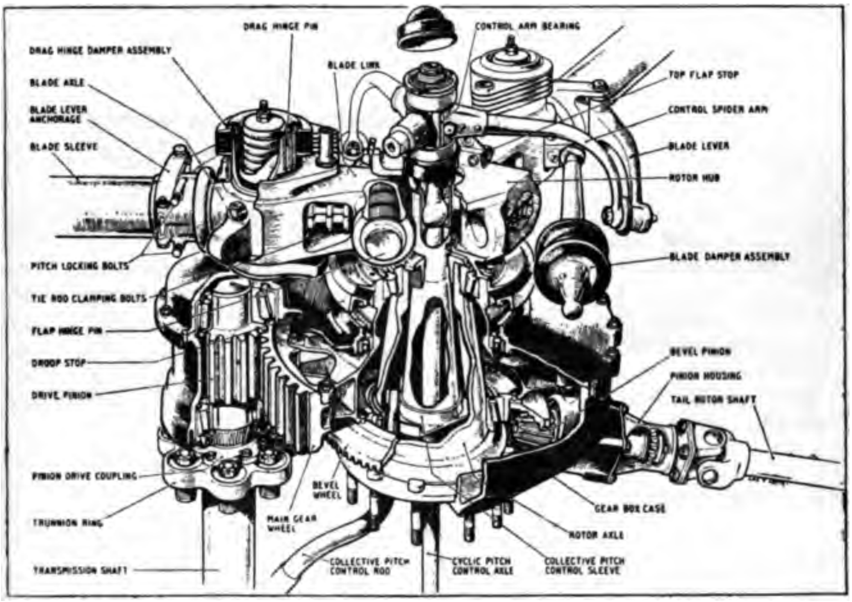
Each blade is secured to the aircraft by means of two bolts passing through a number of horizontal steel plates which are sandwiched between the wooden laminations of the blade root. The removal of one of these bolts allows the blade to be folded for parking purposes.

(*b*) *Main Rotor Hub.*

The main rotor hub is designed to give the blades four degrees of freedom :—

1. About the flapping pin axis.
2. About the drag pin axis (all blades collectively).
3. About the drag pin axis (relative to each other).
4. About the Pitch change axis.

The hub is arranged so that the flapping axes come as close to the rotor centre as possible. The flapping pins have five circumferential grooves which carry in them five rows of needle bearings, and the pins themselves



Bristol Helicopter Type 171, Mk. I. Main Rotor Hub and Gearbox

are slightly barrel shaped so that when they are deformed under load the needle bearings will share this load evenly. A yoke member connects this flapping bearing with the drag bearing which employs two rows of needle bearings. The drag hinge pin also carries the drag hinge dampers which are of the ordinary multiplate friction damper form. The drag hinge stops are arranged to give the two degrees of freedom previously mentioned.

(i) a large movement of all the blades together relative to the hub to permit extreme power conditions as well as auto-rotation in flight, without contact between the blades and the stops and

(ii) a lesser freedom of movement for the blades relative to each other

Bristol Helicopter Type 171, Mk. I with blades folded

which is provided by spacing struts and rubber pads between the blades. The purpose of this is to ensure that the blades are always spaced approximately 120° apart and at the same time accommodate a small relative blade movement which is needed during forward flight.

The third bearing in the blade articulation is the pitch change bearing. This consists of two journal bearings and a tie rod which fulfils the function of a thrust bearing. This tie rod consists of a number of strands or sectors of small cross section which, whilst leaving its tensile strength unaffected, make it torsionally weak in order to permit the changes of blade pitch required for control purposes. The tie rod and the two journal bearings are housed in an inner and outer root sleeve. The outer sleeve being attached to the blade and the outer end of the tie rod, whilst the inner sleeve is attached to the hub and the inner end of the tie rod.

(*c*) *Rotor Controls.*

The outer blade sleeve carries the blade levers which are connected by means of ball joints to the arms of a control spider. This control spider is carried by means of taper roller bearings on a control axle which in turn is universally mounted in the control piston. Now this control piston is moved up and down by means of the collective pitch control terminating in the pitch lever in the pilot's cockpit and the control axle and control spider moves with it thus changing the pitch of all rotor blades collectively. A friction damper is incorporated in this control in order to damp out any small vibratory forces coming from the rotor. If on the other hand the control axle is tilted about its universal joint in any given direction by means of the cyclic pitch control terminating in the control column in the pilot's cockpit, then the pitch of the three blades is changed cyclically, a minimum of pitch being at the point where the spider arms are lowest, and a maximum pitch diametrically opposite to this. An inertia damper is incorporated in this control in order to damp out any slight vibration coming from the rotor control.

Tail Rotor.

(*a*) *Tail Rotor Blades.*

The three tail rotor blades, like the main rotor blades, are made in wooden monocoque construction and are attached to the metal blade root in the same manner as wooden propeller blades.

(*b*) *Tail Rotor Hub.*

The blade articulation for the tail rotor permits blade flapping about a flapping pin employing needle bearings, drag movements on a spherical bearing made of Tufnol and pitch changes on a taper roller bearing.

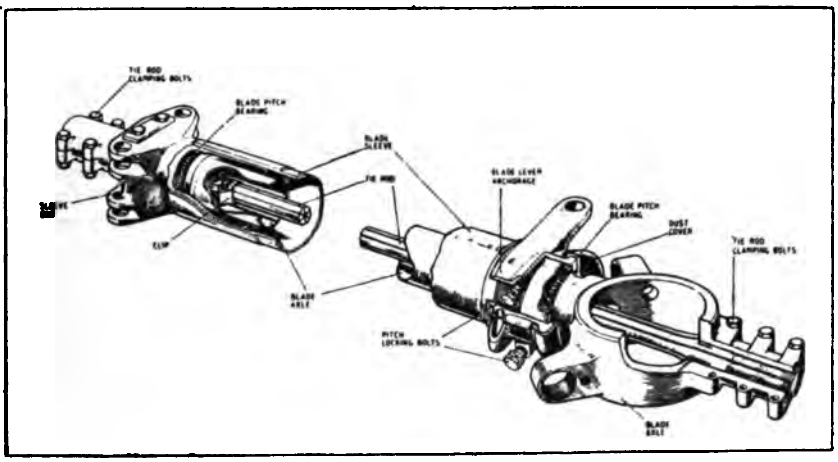
(*c*) *Tail Rotor Control.*

The blade roots carry rigid levers with ball joints, and short connecting rods which are attached to a pitch control spider which rotates with the rotor and can at the same time carry out axial movements which are governed by a quick thread, a sprocket wheel and a chain which in turn is connected by cables to the pedals in the pilot's cockpit.

Power Unit and Transmission.

(*a*) The power unit of the Type 171 Mark I helicopter is a Wasp Junior engine of 450 horse power which has been specially rated to permit over speed at take off and landing which is a safety feature of this helicopter against engine failure. The engine in the Mark I is installed with the crank shaft axis laying fore and aft.

The engine gearbox which contains a spiral bevel drive of approximately 1 in 2 gear ratio, and a single dry plate clutch with automatic engagement by the means of weights acting under centrifugal force, is mounted on the front of the engine and the whole power unit is completely cowled, and fan cooled by means of a fan carried by the flywheel. This cowling is in steel



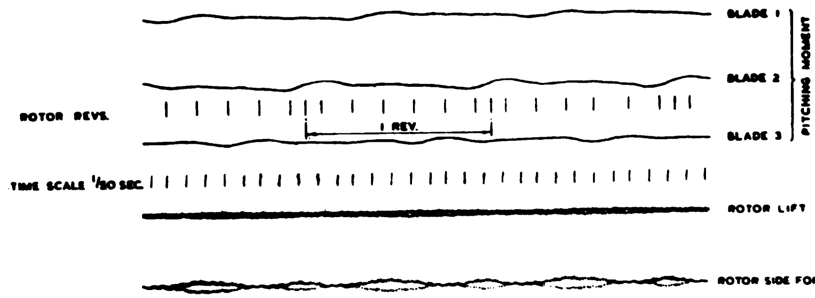
Type 171, Mk. I. Main Rotor Blade Suspension

and fire extinguisher equipment is provided in accordance with standard aircraft requirements. The cooling air enters the fuselage at the top, where it assists in cooling the main rotor gearbox before passing through the power unit and finally through the outlet grill just aft of the main undercarriage. The clutch engagement commences at 900 r.p.m. and the full torque can be taken at 1,200 r.p.m. A free wheel is incorporated within the engine gearbox consisting of an inner driving ring and an outer driven ring. Between the two rings a series of slots and pads are arranged which lock these two rings against each other if torque is applied in one direction, but release them if it is in the opposite direction. The connection between the engine gearbox and the main rotor gearbox is by means of the main drive shaft which is carried between flexible mountings and which incorporates a weak transmission link as an additional safety factor.

(*b*) *Main Rotor Gearbox.*

The main rotor gearbox which is situated immediately beneath the rotor hub, contains a reduction gear, of approximately 1 : 4 gear ratio which, combined with the engine gearbox gives a total speed reduction between engine and rotor of 8.3 : 1.

Straight spur gears are used, the main wheel is carried by a steel axle which is directly attached to the aircraft structure, and the driving pinion is carried by a light alloy gearbox which is attached to the base of the steel axle. This arrangement ensures that deformation due to rotor forces does not affect the gearbox and thus the meshing of the gear. The drive for the



tail rotor is also taken from this gearbox by means of a small spiral bevel gear incorporated in the gearbox terminating in a Universal joint to which is attached the tail rotor shaft.

Splash lubrication is used in the main rotor gearbox except for the top bearing which is provided with a separate oil feed.

The tail rotor drive consists of two steel tubes carried by a number of steadying bearings which lie in the bulkheads of the tail fuselage. These are plain journal bearings allowing axial movement of the shaft. The axial location of this drive is at the knee piece of the tail fuselage, where a double Universal joint is carried between two bearings which ensures constant angular velocity in the drive, which has a maximum speed of approximately 2,000 r.p.m.

Bristol Helicopter Type 171, Mk. I in flight

(*c*) *Tail Rotor Gearbox.*

The tail rotor gearbox contains a spiral bevel gear giving 1 : 1.6 reduction resulting in a maximum speed of the tail rotor of 1,200 r.p.m. The gearbox is made of light alloy and splash lubrication is used.

NOTE.—The power unit for the Mark II Bristol Helicopter is the Alvis "Leonides" engine of 550 horse power, modified for Helicopter operation. This engine, like the Wasp Junior, has been specially rated for over speeding during take off and landing. The engine is mounted in the aircraft with the crank shaft axis vertical and instead of the usual reduction gear it carries directly on the crank shaft a flywheel clutch and fan, and the entire power unit is completely cowled and fan cooled. In the Mark II the main rotor gearbox performs the whole gear reduction between engine and rotor and contains a two stage straight spur gear and a rachet free wheel. The remainder of the transmission is similar to the Mark I.

AIRFRAME.

(*a*) The centre fuselage which is a steel tubular structure carries the main rotor gearbox, the engine mounting, the cabin and the tail fuselage. It is covered by detachable light alloy panels in order to facilitate inspection of this vital part of the aircraft. The centre fuselage rests on a tricycle type of undercarriage consisting of a forward castoring wheel and two rear wheels aft of the C.G. of the aircraft. A parking brake is incorporated in the rear wheels.

(*b*) The cabin consists mainly of Perspex panels and light alloy stringers. A door is provided on either side giving easy access to the seats (with dual controls) in the front and the two rear seats. A fuel tank allowing 2 hours flight is supported by the tubular structure beneath the cabin floor.

(*c*) The tail fuselage is of light alloy monocoque construction of conventional Bristol design. It consists of an intermediate section attached to the centre fuselage, a knee piece which carries a flexible tail skid for the protection of the tail rotor and finally the upwardly inclined tail section. The peculiar shape of this fuselage has been determined by rotor clearance on the one

hand, that is clearance between the blade tip and the knee piece, and the ground clearance for the tail rotor on the other. Inspection doors are suitably placed in the skin to give access to tail rotor shaft bearings and controls.

Before concluding this brief description, I would like to mention a few aerodynamic and other significant features of the Type 171. The most outstanding is its high rotor tip speed. I have always held very strongly the view that the obstacle to high forward speed of the rotating wing is vibration due to dissymmetry in the rotor disc caused by :

(1) The excessive tip speed ratio which gives lateral dissymmetry in the form of a high speed for the advancing blade and low speed for the retreating blade.

(2) The excessive coning angle giving longitudinal dissymmetry in the form of a low inflow angle at the forward part of the rotor and a high inflow angle aft.

These features must be avoided as far as possible and this can best be done by the use of high tip speeds. GLAUERT's figure of merit has often been quoted as a criterion for rotor efficiency ; indicating low tip speeds and a high thrust coefficient. This argument applies, however, only to the hovering rotor whereas the criterion in forward flight is essentially the stalling of the retreating blade. The stalled area of the rotor disc increases with the product of thrust coefficient and tip speed ratio and it can be shown that if the tip speed ratio exceeds the value of .4, the mean profile drag coefficient increases dis-proportionally and with it the power expended in rotor drag. It is therefore, profitable to increase the rotational speed of the rotor rather than the tip speed ratio. There is of course a limit to such increase of rotor speed, which is governed by the resultant speed of the advancing blade tip. When this reaches a critical value shock stall will develop and one is thus confined to operating between these two limiting conditions which approach one another with increase of forward speed until eventually the ultimate limit is reached where blade stalling at the retreating blade and simultaneously shock stalling at the advancing blade is experienced.

The Bristol 171, I believe, is the first helicopter for which these limitations have been seriously considered. We have actually achieved a Mach No. of nearly .75 as a combination of about 110 m.p.h. forward speed and a rotational speed of 264 r.p.m.

The Bristol 171 rotor can operate very close to the ultimate limit of conditions and it is hoped that the Mark II of this type which will have metal blades will be able to fly at a speed of about 140 m.p.h.

There is at present, due to manufacturing errors in the wooden blade, a one per rev. oscillation at high forward speed, but we have not yet experienced the critical once per blade oscillations.

In conclusion I would like to revert to the analogy in my opening remarks. The fruitfulness of the expedition has been mainly due to one factor, which is important to any such undertaking, a good team spirit. It has been a large team and there is not time now to mention names, but I would like to take this opportunity of thanking all those who by their unfailing effort and co-operation have made this venture such a success.

THIRD LECTURE, 1948.

Some Technical Aspects of W.9 Development

By J. S. SHAPIRO, A.F.R.Ae.S.

A lecture illustrated with slides and delivered before the Helicopter Association of Great Britain on Saturday, 3rd April, 1948, at Manson House, 26 Portland Place, London, W.1.

H. A. MARSH, A.F.C., A.F.R.Ae.S., IN THE CHAIR

It is regretted that owing to lack of space the lecture could not be published in full and as there was insufficient time for the lecture to be rewritten the following is published as " EXTRACTS FROM THE TEXT."

INTRODUCTION BY THE CHAIRMAN.

LADIES AND GENTLEMEN,—A number of you may not know our lecturer of this afternoon and I am glad to be able to tell you something of his past experience by way of an introduction.

Mr. SHAPIRO has had several years of engineering experience and his first aircraft appointment was in France working on the design of gyroscopic instruments, which post was rudely terminated by happenings in 1940. He came to this country and joined Power Jets, working on jet propulsion and then had a further period on aircraft instruments design. This was followed by work on electric assister units for aircraft before he joined the Cierva Autogiro Company in 1943 as Senior Technical Officer.

Mr. SHAPIRO is a Founder Member of our Association, an A.F.R.Ae.S. and holds an engineering diploma of the Federal Polytechnic in Zurich.

It was intended that he should tell us something of the problems of multi rotor design, and it is due to circumstances beyond his control that the subject had to be changed at a late date and he will now talk instead on " Some Aspects of W.9 Development."

It is again a pleasure to welcome our guests today on behalf of the Association.

MR. J. S. SHAPIRO.

MR. CHAIRMAN, LADIES AND GENTLEMEN.

I am going to report this afternoon on some experiences with an experimental helicopter. Considering the rapid progress in this art, I may call them early experiences. Some of the conclusions which you will hear to-day

have been generally accepted, others are controversial, but all must be judged in their context, having regard to time and circumstances.

THE TORQUE EQUILIBRIUM OF SINGLE-ROTOR HELICOPTERS AND THE CONTROL FORCES IN TILTING HUBS.

Static Equilibrium of a Helicopter.

Figures 1 and 2 show a hovering helicopter and illustrate the principal forces acting on it. The torque reaction, being, together with the lift, the resultant of all aerodynamic forces acting on the rotor, is represented by the moment vector Q_R. This vector is a free vector and defines direction and magnitude only and not a line of action. It is, therefore, depicted along an arbitrary line *normal* to the tip path plane of the rotor.

For the sake of simplicity it could be taken, to start with, that flapping hinge off-sets are absent, and we are, therefore, entitled to assume that the resultant rotor thrust goes through the centre of rotation. As regards the precise direction of the thrust vector, we can again make assumptions identical with those relating to the resultant torque vector.

Static equilibrium of a hovering single-rotor helicopter, as that of every free body, requires the fulfilment of six equilibrium conditions expressing the absence of resultant force and moment components.

Most of these conditions are trivial but some deserve mention. For simplicity, minor inaccuracies are covered up by the following, somewhat loose, terminology—

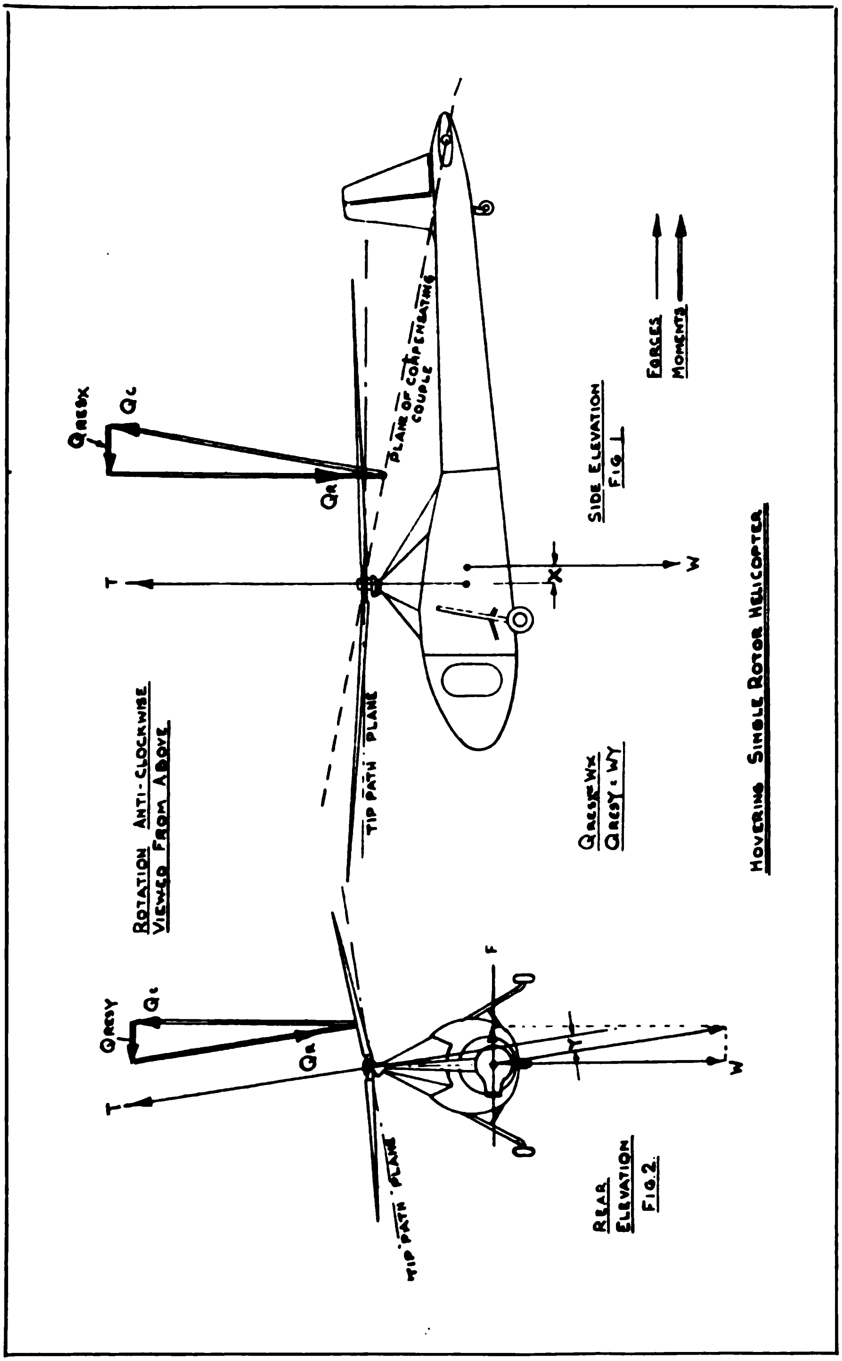
As easily seen in Figs. 1 and 2, rotor thrust balances the weight of the aircraft. The thrust is vertical in the pitching plane (Fig. 1), but in the rolling plane (Fig. 2) a lateral thrust component has to balance the tail thrust F. Whilst this tail thrust is represented as being generated by a reaction jet, this is by no means an essential feature of the present argument.

Moment equilibrium is established as follows. Q_R is the rotor torque reaction. The moment vector Q_C, representing the couple between tail force and lateral thrust component, which, again, is a free vector, is shown along a line intersecting the line of the moment vector representing torque reaction, and the direction of the compensating moment is at right angles to the plane defined by the line joining the rotor centre with the centre of the tail thrust and by direction of the tail thrust itself.

The main thesis of this chapter is a fact of elementary simplicity, but too often overlooked, that the compensating couple can only fully balance the rotor torque reaction when their two lines of action are parallel and that, consequently, if an angularity exists between the two lines of action, an unbalanced moment is present which we have termed 'residual torque' and which may have pitching and rolling components.

It is clear that since the direction of the rotor torque reaction depends on the tip path plane and the direction of the compensating moment depends on a plane defined by the aircraft, the residual torque is varied whenever the tip path plane is displaced with regard to the aircraft.

Furthermore, any increment of residual torque, caused by an angular displacement of the tip path plane, acts about an axis at right angles to the

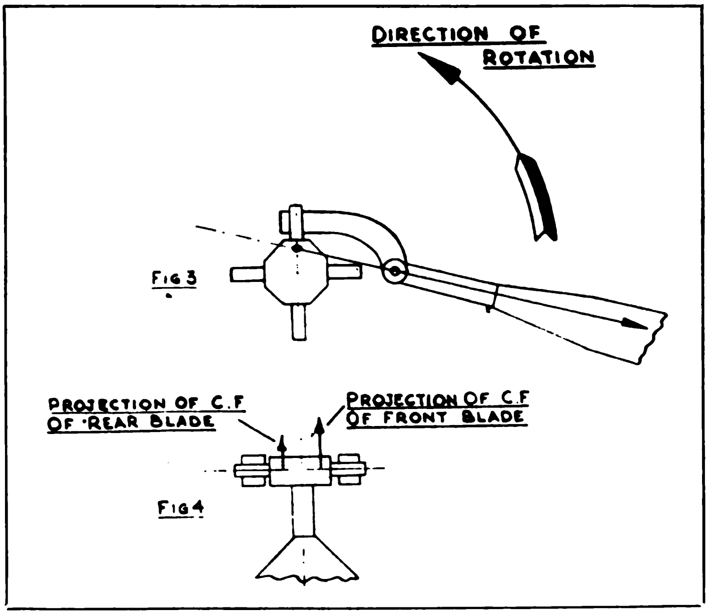


HOVERING SINGLE ROTOR HELICOPTER
SIDE ELEVATION
FIG 1
REAR ELEVATION
FIG.2.
ROTATION ANTI-CLOCKWISE VIEWED FROM ABOVE
TIP PATH PLANE
PLANE OF COMPENSATING COUPLE
FORCES
MOMENTS
QRESX = WX
QRESY = WY
QRESX
QRESY
QC
QR
T
W
X
Y
F

axis about which the inclination of the tip path plane takes place. These relationships are quite fundamental and entirely independent of the control system of the rotor provided only that direct control is applied, *i.e.*, the rotor is displaced relatively to the aircraft. Residual torque components in pitching and rolling must be compensated by pitching or rolling couples if equilibrium is to be maintained. These can only be generated by off-sets between the line of action of gravity applied at the c.g. of the aircraft and the line of action of the rotor thrust applied at the rotor centre (See Figs. 1 and 2).

Forces in Direct Rotor Controls.

To examine the influence of these relationships on control forces it is now assumed that in a certain position which may correspond to the neutral stick position, the hovering helicopter is in equilibrium and, for the sake of generality, it may be assumed that this equilibrium is associated with pitching and rolling moments balanced by the above off-sets. We now proceed to incline the rotor by application of control in the pitching sense and it follows from the above that, before motion sets in, apart from an unbalanced pitching moment which is the primary purpose for applying pitch control, a rolling moment is also generated. Whilst the pitching moment is proportional to the thrust and the change of tilt in pitching, the rolling moment is propor-



tional to the torque and equally, to the change of tilt in pitching. Up to this point we have ascertained that the rolling moment always finally acts on the aircraft but it depends on the control system in what way this rolling moment is transmitted.

It is further concluded that in a cyclic pitch controlled rotor this rolling moment increment is transmitted entirely through the mechanical axis of

the rotor and through its bearings to the aircraft. However, when the rotor is controlled by tilting, the rolling moment increment, arising as a consequence of pitching inclination of the rotor tip path plane, is transmitted partly through the mechanical axis and partly through the control mechanism itself.

The former statement can be very easily illustrated by representing the rotor by the centrifugal forces of the blades acting along their longitudinal axes, this being a very useful pictorial simplification adequate in most instances. Inclination of the tip path plane is identical with first oder flapping which causes the longitudinal axes of the blades to have different vertical components on both sides of the rotor. Since these components act at an off-set from the axis of rotor due to the torque, the presence of a lateral or rolling moment is immediately visible when fore and aft flapping takes place. (Figs. 3 and 4).

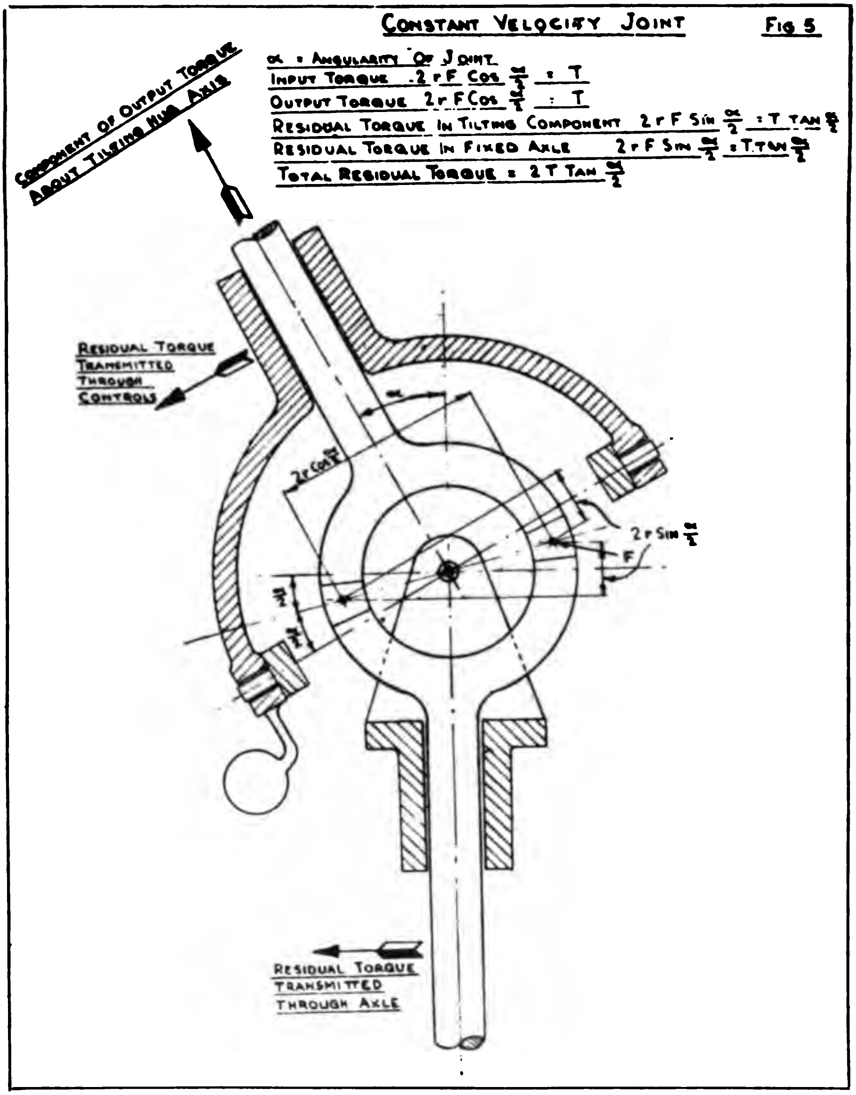
To find the proportion in which residual torque increments are transmitted directly to the aircraft or indirectly through the control mechanism in a tilting rotor, we have to examine the torque transmission mechanism of the rotor. In the first place, we examine a constant velocity joint in which torque is transmitted through pressure elements always maintained along the line bisecting the angle between the input and output shafts of the joint. It is clearly seen from the diagram in Fig. 5 that half the residual torque is transmitted through bending of the input shaft and the other half appears as a lateral tilting moment acting on the output shaft, and therefore, loading the control mechanism.

If, instead of a constant velocity joint, an ordinary Hook's joint is used, the proportion of the two moments varies periodically between two extremes in one of which the entire residual torque is transmitted as bending of the input shaft and in the other the entire residual torque is transmitted as a lateral tilting moment on the tilting hub and hence as a control force.

Among various arrangements examined is one in which the rotor is tilted together with the main speed-reducing gear box ; in such a case the only forces arising from the drive are those associated with high speed torque and these are only of secondary importance. It can then be demonstrated, however, by examining the gimbal mechanism on which the rotor with its gear box is suspended, that, on the average, half the residual torque will still be transmitted through the control linkage.

It ought to be emphasised that since the total travel of a control column is a constant determined by the pilot's convenience, maximum stick load is proportional to the square of the angular range associated with maximum stick travel. In view of this quadratic relationship, it is impossible to predict the forces in a tilting control without precise knowledge of the required range of tilt, which can only be found by experience or comparison with other helicopters.

From the pilot's point of view the transmission of part of the residual torque through the control mechanism is felt as a control force at right angles to the stick movement. Though the control force as such can be eliminated in an irreversible mechanism, an unbalanced resistance to the application of control remains. For instance, whilst a certain amount of fore and aft control is maintained, an application of control to port has to



overcome the control force due to residual torque, whilst an application of control to starboard is aided by residual torque.

Powered Control Systems.

Given the range found necessary to control the W.9 machine, the control forces due to residual torque can be shown to exceed the permissible level for precise and comfortable response by the pilot. They represent the only aspect in which a tilting power driven rotor is fundamentally different from a similar autogiro rotor.

Among other causes responsible for control forces, there is friction which, in some autogiros having plain bearings for flapping hinges, has been responsible for excessive control forces. This is not the case with rolling bearings and the needle bearings provided in the W.9 are quite adequate for this duty. However, in a rotor with flapping hinge off-set the presence of flapping, such as in forward flight conditions, causes a biasing moment transmitted through the control linkage in a tilting control. This biasing moment, in contrast to that arising from residual torque, is partly in phase with the control displacement. It can be used to provide a measure of "stick free" static stability. Its neutral position and characteristics can be, to a large extent, controlled by selection of the tilting hinge of the rotor. The stability aspect was not intended in the W.9 machine. It could not be used because of the large forces involved and originally also because of the out of phase component of biasing moment.

At that stage the order of magnitude of control moments was investigated on reasonable assumptions under adverse conditions, mainly high speed forward flight, and it was found that moments of the order of 200 or 300 lb. ft. occurred due to residual torque and moments of the order of 400 to 500 lb. ft. occurred due to flapping hinge off-set, the latter moment, originally found to exist in equal measure in both rolling and pitching could, later on, with the introduction of the compound back coupling linkage, be confined to pitching moments only.

By suitable positioning of the rotor centre against the c.g. of the aircraft and suitable arrangement of initial angularity of the drive, maximum moments could be reduced to half the above value. It is clear, however, that moments of this magnitude are beyond the power of a human pilot.

It was decided to apply a powerised control system installation which had been contemplated from the beginning. Upon examination it became evident that the most elegant solution, from the mechanical point of view, was a hydraulic assister unit on the follow-up principle and the unit chosen was a pair of Lockheed "Servo-dyne" jacks which are hydraulic servo motors characterised by the following features :—

(*a*) Positional correspondence is ensured by placing the follow-up valve on the moving part of the servo motor and arranging the pressure and return lines through flexible hose connections.

(*b*) Double action is obtained by arranging different effective piston areas for the two senses of motion and maintaining continuous pressure on the smaller area, whilst controlling, on and off, the larger area.

(*c*) The "Selector" or follow-up valve is of the poppet type and the fluid pressure is counteracted by spring loading of the valve elements.

This last feature is responsible for an extremely small lost motion (of the order of 3 thou.) but calls for a comparatively large input force to control the "selector" valve.

Though in the course of flight testing there have been many modifications to mechanical details such as lever ratios, selector valve spring loading, and ratio between pitching and rolling control, the assister unit installation can be regarded as a complete success. In spite of initial "sales" resistance the test pilot became accustomed to the feel, or rather lack of feel, of

an assisted control mechanism of this type and the control force could be adjusted to suit the pilot's convenience. After several dozens of hours of flight and operations on the ground involving an estimated number of control movements running into several 10,000's, no mechanical trouble of any kind has been experienced with the installation.

Torque Compensation by Tail Jet using Engine Waste Heat. Response to Yawing Control.

The basic conception of a tail jet is simple and no different fundamentally from the tail airscrew. Physically, both forms of thrust generating devices embody the reaction principle and are subject to the law that thrust is proportional to the square of the velocity of the reaction jet and the power expended to generate the thrust is proportional to the cube of that velocity and it is, therefore, more advantageous to work with low velocities. Hence, to attain a given thrust, both mass flow and area of jet must be as large as possible. One difference between airscrew and jet is that the effective area of the jet may be equal to that of a (well designed) orifice, whereas the area of the airscrew slip stream is only half the disc area of the airscrew.

It follows from this simple consideration that, given equal conditions, an airscrew will be more efficient as it is quite impossible to design jet orifices even approaching half the size of a reasonable airscrew disc area. Conditions, however, are not equal in several respects.

1. The required magnitude of thrust for torque compensation naturally depends on the distance of its line of action from the axis of the rotor. It is quite conceivable that an orifice may be placed further out for an equal weight of tail structure as compared with an airscrew involving a concentrated weight and giving rise to vibrations.
2. It is possible to improve jet performance by the addition of waste heat from the engine. Although the amount of heat is large, the benefit from the addition of heat depends entirely on the pressure level at which it is added. The highest pressure level can only be equal to the dynamic head of the reaction jet. It is clear, therefore, that a larger, and therefore more efficient orifice, leads to a reduced benefit from the addition of heat.
3. The very size of the tail airscrew makes it necessary to raise its axis, mainly to enable the helicopter to carry out certain manoeuvres near the ground which require a tail-down attitude. Such raising of the airscrew axis is accompanied by additional weight, which is equivalent to additional power.

The jet reaction system was mainly proposed for reasons other than performance considerations, principally for the sake of avoiding vibrations in forward flight and for safety near the ground. The latter feature undoubtedly remains a valid argument in favour of a jet, but it is felt that, in the meantime, designers of tail airscrews have succeeded in eliminating vibrations peculiar to that source and it can no longer be regarded as an argument against the tail airscrew. The original opinion that a jet offers

less drag in forward flight is totally wrong. Although a jet installation lends itself more easily to the arrangement of a fin which can furnish all the torque reaction required at and above cruising speed for approximately 2—2½% of total power, with due refinement a tail airscrew may furnish the equivalent of 1 or 2% in the form of thrust. It is seen, therefore, that this aspect is altogether marginal.

Summarising, it can be said that the jet system, when properly laid out, is marginally inferior in performance, but offers safety to personnel on the ground.

It is, however, in the *control* of the tail jet which constitutes the yawing control of the aircraft that the greatest difficulties arose. The original design was arranged to provide a throttling control on blower intake by moving shutters. This proved to be a problem in mechanical design which could only be satisfactorily solved by the addition of considerable weight. It was also realised that any type of throttling control, whether applied to blower inlet or orifice outlet, would require a continuous power input to the blower corresponding to the highest value of thrust required at any time during the application of the yawing control. Experience showed that the variation of thrust for yawing control comparable to control by tail airscrew required an increase in tail thrust of the order of half the average value for torque compensation in hovering. The power increase is even greater than the percentage of thrust increase and 50% of increase in thrust would amount to 84% increase in power, which, in the circumstances, was not acceptable.

These considerations led to the construction of a variable pitch fan of all metal design which was fitted to the machine. Although a mechanical solution for controlling the torque reaction jet was thereby fully achieved, the method of jet control " at the source " proved to be inadequate in comparison with the yawing control provided by a variable pitch tail airscrew.

The disadvantages attributed to this form of control are as follows :—

1. The control is sluggish, that is, its effect is felt after an appreciable lapse of time following the application of control. In view of lack of measurements, it is difficult to state in terms of physical magnitudes what precisely is the meaning and magnitude of the time lag and whether the sensation of angular acceleration or the observation of the change of position is predominant but, for what it is worth, the pilot states that the delay in control effect is of the order of 1 to 2 secs. The cause of this delay is believed to be due to the compressibility of the air and must depend on the cubic capacity of the tail which acts as a pressure vessel. In fact, were the air incompressible, an increase in blade pitch would produce an immediate rise in pressure throughout the tail and the jet would commence accelerating immediately until the jet velocity acquires a new equilibrium value. The period of acceleration already constitutes increased thrust. It is clear that the chief weakness of the W.9 installation, in having the blower mounted very far forward, was a feature greatly contributing to this particular disadvantage of yawing control by jet reaction.

2. Whilst the continuous expenditure of power by jet torque reaction may, as mentioned previously, be justified on performance grounds alone when everything is taken into consideration, such an increased expenditure of power per unit of torque causes large power variations to accompany an application of yawing control. The effect is inseparable from any type of torque compensation involving the expenditure of power unless special interlinkage mechanisms are used. The magnitude of the effect may make it irksome to the pilot, especially if he is used to a different level of variation.

Undoubtedly, the combination of the two disadvantages is an added difficulty for the pilot because, in the attempt to reduce the control lag, he increases the amount of control unnecessarily and thereby aggravates the interference with rotor power.

Hovering Stability of Helicopters with Rotors having Pronounced Flapping/Pitch Coupling.

At the time when the following investigations were made, hovering stability of helicopters was known in its application to machines with counter-rotating rotors of the superimposed or side-by-side types. Such machines offer, in principle, a substantial simplification of analysis due to the fact that hovering stability can be examined separately in the two principal planes of the machine, namely the pitching and rolling planes. A further simplification is made if blade flapping or, what amounts to the same, the inclination of the tip path plane is not considered a separate degree of freedom. Hovering stability then involves only two degrees of freedom, namely fore and aft movement and tilting in pitch of the whole aircraft, and leads to characteristic equations of the cubic type which can be solved with very little labour.

The elimination of flapping as a degree of freedom implies that the tip path plane adjusts itself to the general motion within a time interval of negligible length in comparison with the natural period of the general motion. Flapping, therefore, enters the picture only in its effect on the derivatives of the rotor force and moment with regard to motion in the two degrees of freedom.

In actual fact, in a single-rotor helicopter, there is no inherent reason to separate the pitching and rolling planes. There is, in fact, a side force generated by forward motion and vice-versa. In what follows it will be seen that these " cross " forces and moments are of decisive importance in a single-rotor helicopter from the point of view of control and the development of the " compound back coupled " rotor can, from the point of view of stability and control, be simply expressed as the elimination of coupling between the pitching and rolling planes of motion (or any other two planes through the vertical axis of the machine normal to each other).

In the first place, a considerable amount of work was done whilst *disregarding* the coupling terms in an endeavour to establish stability and control features derived from the " flat tracking " properties of the rotor irrespective of phase relationships. It was subsequently found that the conclusions reached from such investigations can be applied, without modification, in principle, to a practical rotor in which the coupling is *eliminated* instead of being *disregarded*. We shall, therefore, regard the

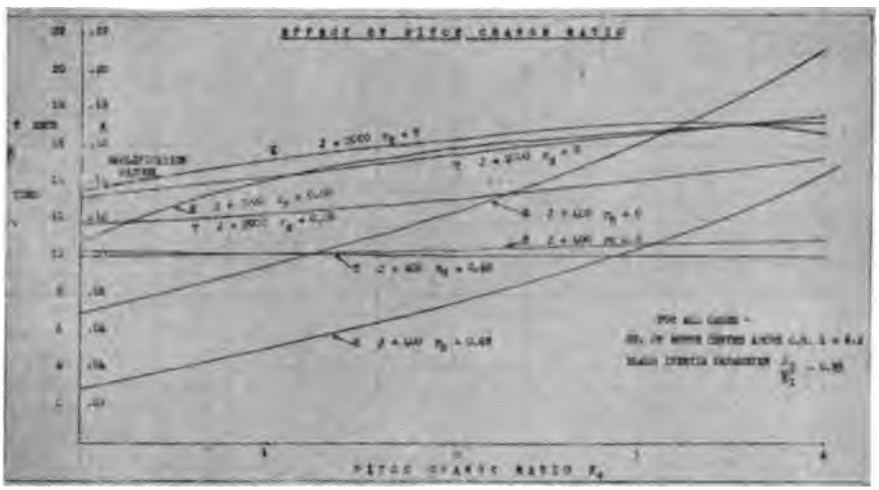
results as applying to a " flat " tracking rotor of any description, that is a rotor in which the flapping is automatically substantially reduced as compared with a freely flapping rotor.

As is well-known now, single-rotor helicopters are generally unstable in hovering in the sense that, when left to themselves after a disturbance, they carry out an oscillating movement involving both tilting and fore and aft translation which motion is self-excited and has a natural period measured in seconds and a rate of amplification which depends to a large extent on the design parameters.

The investigation was concerned with the influence of important design parameters on the amplification factor and the natural period of the free motion of the machine. Most of the conclusions are to-day well-known and have been verified by various investigators so that emphasis is put here on the effect of " flat tracking."

Before dealing with the influence of " flat tracking," we must point out, however, one feature which is usually surprising to designers, namely that high inertia of a machine has a destabilising effect in the sense of increasing the amplification factor. Although high machine inertia also increases somewhat the natural period and makes it, therefore, easier to deal with instability, beyond a certain machine inertia all other design parameters become of decreasing importance. Expressed in practical terms, there is likely to be less difference between single-rotor helicopters in the pitching plane than in the rolling plane.

W.9 Stability in Hovering.



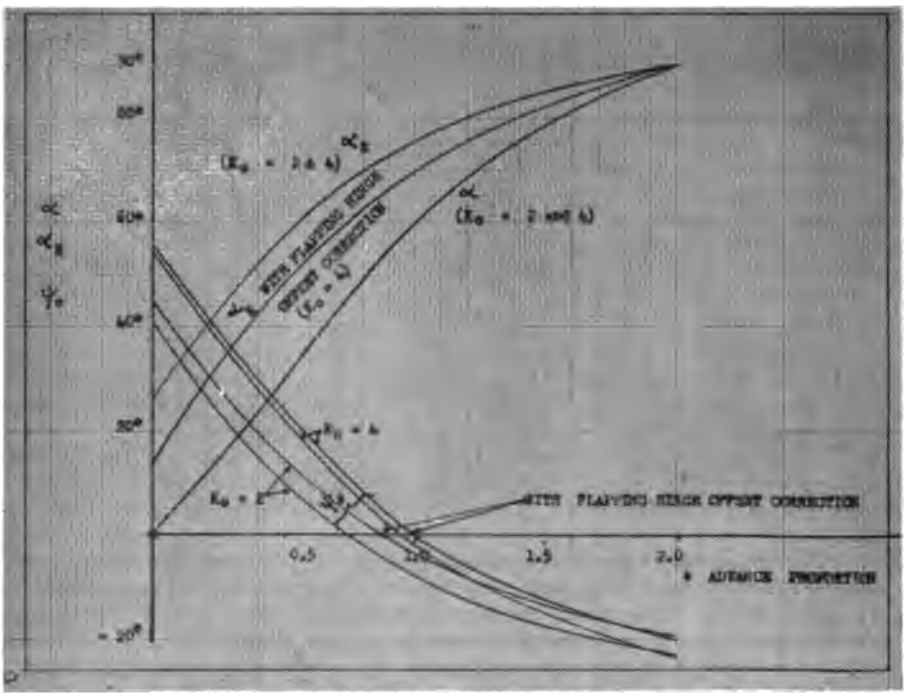
The main result of this investigation is the destabilising effect of " flat tracking " expressed in a linear increase of the amplification factor with the pitch change ratio, whilst the natural period remains almost unaffected. This is particularly visible with low machine inertia (rolling). The result is surprising in a sense, and emphasises the importance of investigating the machine as a whole rather than the rotor itself. In visual terms, it points

to the completely misleading nature of observations made on a model when the hub is rigidly mounted. In such a model a high negative pitch change ratio, by making the rotor more "flat tracking" and reducing the oscillations of the tip path plane caused by casual disturbances in the wind tunnel, produces the impression of stability. It is this apparent stability which has led to the expression "gust stability," and whilst it is true that in a rotor with a high pitch change ratio the rotor plane is less disturbed in relation to the hub, this does not mean stability of the machine as a whole, but the very opposite.

Related to more systematic investigations leading to explicit expressions for the amplification factor, it can be said that the moment derivative of tilting motion and the force derivative of translational motion have a stabilising effect whereas the moment derivatives of translational motion and the force derivatives of tilting motion have a destabilising effect. Numerically, both moment derivatives are the more important ones. Roughly speaking, the main effect of a negative pitch change ratio is to reduce both moment derivatives. It has, therefore, both a stabilising and a destabilising effect. However, in a first approximation the amplification factor is proportional to the moment derivative of translational motion and inversely proportional to the square of the moment derivative of the tilting motion. The nett effect of a negative pitch change ratio is, therefore, destabilising.

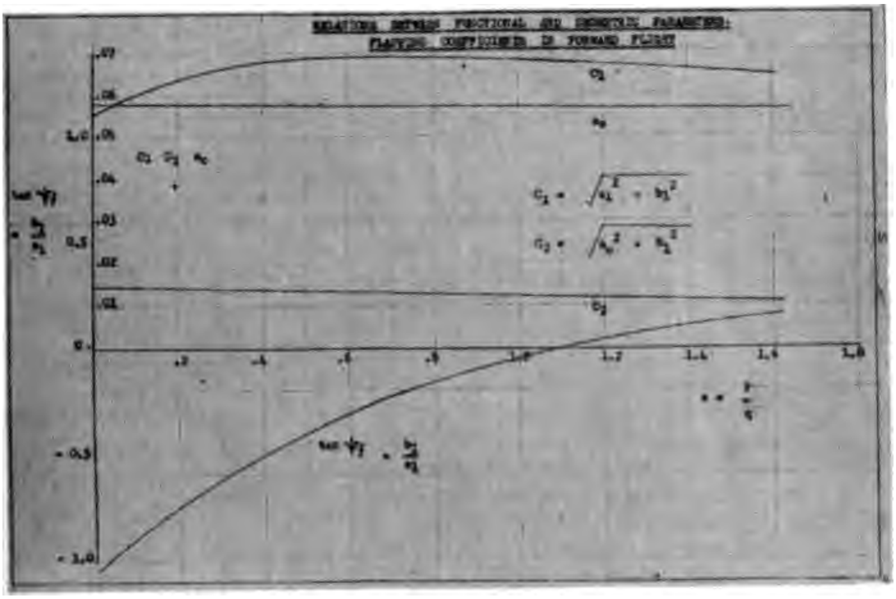
W.9 Compound Back-Coupled Rotor.

Relations between Functional and Geometric Parameters.



It is known that these investigations were based on several approximations. It has already been mentioned that flapping as a separate degree of freedom was eliminated. The vertical and yawing degrees of freedom were also neglected. Both these approximations are amply justified. Furthermore, the resultant rotor force was assumed to be normal to the tip path plane and, moreover, in the tilting motion no dissymetry of the slip stream was considered. Both approximations are unjustified, and have been corrected by a more exact treatment. The results suggest that numerical values are

W.9 Compound Back-Coupled Rotor.



sufficiently modified to make it desirable to avoid the last two approximations wherever the actual magnitudes are of importance, but neither of these approximations is responsible for a shift of emphasis in the general conclusions reached.

However, the disregarding of coupling between the pitching and rolling planes, in the presence of a high negative pitch change ratio which produces considerable out of phase flapping in rotational and translational motion appeared to be totally unfounded and an investigation was carried out taking into account all four degrees of freedom. The equations of motion led to four simultaneous differential equations, the characteristic equation of which was of the sixth degree. Numerical values were introduced and applied to the W.9 machine, but, for the sake of generality, the method of flapping reduction remained unspecified and was merely introduced by a coefficient expressing a reduction of flapping in phase with the direction of motion to 1/3 of the freely flapping rotor. The out of phase component of flapping was given values beginning with 0 and ending with a component of equal magnitude to the in-phase component. The

coefficients of the sextic were plotted against the ratio of the derivatives in the two phases and most coefficients found to be symmetrical about the zero value. The numerical solution of the sextic was carried out by the Mathematics Division of the N.P.L. and the results showed that no critical increase in instability was introduced through the coupling between the rolling and pitching planes. On the contrary, the highest amplification factors were reduced by the existence of the coupling which signified, as it were, that the lower instability in the rolling plane and the higher instability in the pitching plane are mixed into an intermediate instability when the two planes are cross-coupled.

RESPONSE TO AZIMUTH CONTROL OF HELICOPTER. WITH TILTING ROTOR AND PRONOUNCED FLAPPING-PITCH COUPLING.

The investigations summarised under this heading are concerned with the behaviour of a helicopter arbitrarily constrained to tilt about an axis through its c.g. This axis can coincide with the pitching or rolling axis and, to be specific, the pitching axis was chosen. In this instance, the flapping of the blades expressed by the inclination of the tip path plane was considered a separate degree of freedom. The motion, therefore, consists of two degrees of freedom, viz., rotation of the machine about a horizontal axis through its c.g. and inclination of the tip path plane relative to a chosen reference plane fixed in the machine.

Viewed in this light, it is immaterial whether out of phase flapping exists and the investigation does not reveal its effect. Consequently, results reported here are the same whether we disregard the out of phase flapping or eliminate it through a compound linkage.

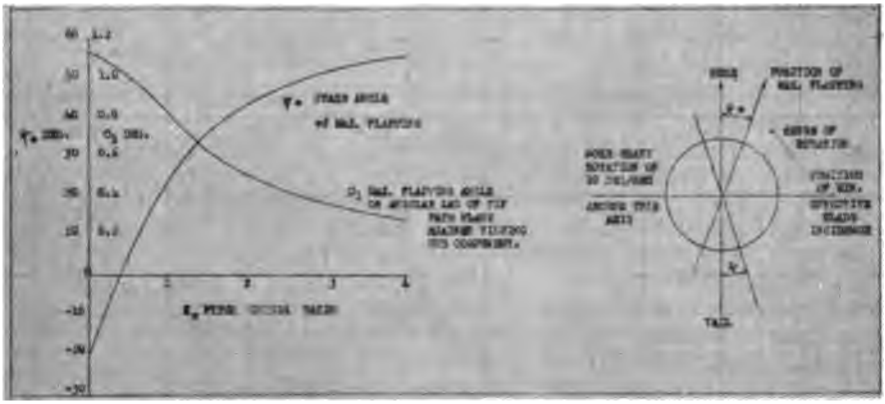
Apart from the existence of cross coupling between the pitching and rolling planes, these calculations also exclude the translational motions to which the real machine is subject once the hovering equilibrium is disturbed by the application of control. Furthermore, the calculation assumes that a control displacement is completed instantaneously.

At the time, the calculations were carried out to crystallize the influence of control parameters in the comparison between hovering helicopters of various types. It is believed that the results do, in fact, reveal significant features and measure magnitudes of real value in judging the control of a helicopter. The reason is that control displacement can be applied within time intervals which are negligible compared with the duration of motions here considered and that the first few seconds of the motion of the machine initiated by a control displacement are unaffected by the interaction between the translational and rotational degrees of freedom. On the other hand, the existence of out of phase force and moment components has proved to be a decisive feature causing inability of the pilot to control the W.9 machine in hovering until these out of phase forces and moments were substantially eliminated. This aspect will be discussed fully in the next chapter.

Perhaps it is profitable to proceed from the physical aspect. It would seem that the essential difference between control by cyclic pitch change and hub tilting, when both are associated with flapping hinge off-set, is that, in the cyclic pitch controlled rotor, the tip path plane is tilted first, and as soon as the tip path plane is inclined, the centrifugal force of the blade exercises a so-called T bar effect on the hub, producing a powerful moment

in the same direction as the moment of the resultant rotor thrust about the c.g. of the aircraft. When the aircraft attains a certain rate of pitch this rate causes a backward inclination of the tip path plane and angular acceleration ceases when the backward inclination restores the tip path plane to a position where the moment about the c.g. vanishes.

W.9 Rotor System.
Flapping Coefficients during 10 deg./sec. Tilting Motion.

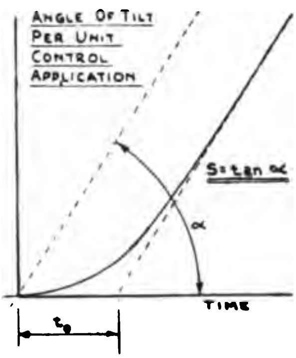


When, on the other hand, the hub is tilted, during the initial period, the tip path plane has not moved yet the " T bar effect " works the opposite way and the machine actually experiences a reverse acceleration to start with In the next phase, the tip path plane has followed the hub and exercises a moment by virtue of the inclination of the left vector but without T bar effect. Finally, equilibrium sets in when the same condition is fulfilled as above.

The main object of these calculations was to establish whether the initial period of acceleration is responsible for a difference in behaviour which is likely to affect control from the pilot's point of view. The result of the calculations can be expressed numerically in a very simple way. A given amount of control displacement corresponds to a steady rate of tilt to which the machine settles down, asymptotically. A line, representing

MACHINE CONSTRAINED TO ROTATE ABOUT PITCHING AXIS THROUGH C G

HINGE OFFSET r_H	FLAPPING REDUCTION K_c	TILTING S	TILTING t_0	CYCLIC S	CYCLIC t_0
0	0	8.32	1·60	8.92	1.60
0·68	0	4.31	0.965	8.92	0.81
0.68	2	9.3	1.71	19·25	1·67



this rate of tilt in a graph giving the angle of tilt upon time, cuts the time axis at a point which can be taken to represent the initial delay between the instant of application of control displacement and its effect on the machine. An illustration shows initial delay and rate of tilt almost identical in the R.4. and W.9 machines and gives an idea of influence of flapping hinge off-set and pitch change ratio. It is seen, for instance, that an increase in flapping hinge off-set reduces the rate of tilt in the tilting hub controlled machine but has no effect on the rate of tilt in a cyclic pitch controlled machine. A pronounced negative pitch change ratio increases both the rate of tilt and the initial delay in a tilting hub controlled machine and has the same effect on a cyclic pitch controlled machine. The latter combination, incidentally, represents a hypothetical rotor not attained by any known blade articulation.

These investigations showed further, when compared with the calculation of instability, that in a W.9 type of hub, all parameters which reduce instability, such as larger hinge off-set, lower pitch change ratio and higher blade inertia, also slow down control response, in the sense of reducing the rate of tilt. But rotor height (above c.g.) when increased up to a certain limit marginally reduces instability and quickens control. Machine inertia whose increase makes instability worse, has no effect on control rate of tilt but increases the initial delay following the application of a control displacement. These results apply to a tilting hub. With cyclic pitch control an increase in flapping hinge off-set both reduces instability and quickens the control response.

Compound Back Coupling Linkage.

In this context the relevant aspect of this linkage is its functional purpose. This can simply be described as a mechanism ensuring the absence of out of phase components of forces and moments in the motion of the rotor following the application of control. It can equally well be described as the elimination of " cross " derivatives in free rotor motion, for example, translational movement of the rotor in a direction X produces forces and moments on the machine substantially only in the plane containing the rotor axis and the direction X. A simple flapping rotor without coupling between pitch change and flapping fulfills this condition, though not accurately, but to an acceptable degree.

In view of many misconceptions encountered since the introduction of this linkage it is desired to emphasise that it differs from the simple pitch/flapping coupling only in the presence of rotor motion. Once that motion ceases, or if no such motion can take place, both the simple pitch flapping coupling and the compound linkage produce the identical result—namely, that upon the application of a control displacement, the rotor, after a very brief transient, but highly stable motion, settles down to a new position in strict sympathy with the control displacement in magnitude and direction. It is clear, therefore, that the difference could hardly be discovered by merely observing the manner in which a model rotor, mounted on a rigid base, follows the application of tilting control.

Further, the effect of out of phase forces is clearly a matter of degree. No rotor system can eliminate all " cross " components under all conditions and the degree to which such rotors have been flown successfully

shows that " cross " components, up to a certain magnitude, are acceptable. This aspect emphasises the importance of a practical flight test since in involves the translation of human reactions, in a manner not hitherto generally explored or summarised, into physical magnitudes. It is clear, therefore, that had attention been concentrated from the start on the phase aspect of rotor response to motion and control, there would be no means of telling whether " cross " components were excessive or not except by a practical flight test in full scale.

In fact, to some extent, calculation would have been misleading as analysis would have to concentrate on the instability which, as was proved later, does not deteriorate in the presence of " cross " derivatives.

The choice of means for the elimination of " cross " components was dictated by mechanical considerations, having regard to the design of the existing hub. The " compound back coupling linkage " constitutes one such method which has the advantage that, from the mechanical aspect, it is no more complicated than the simple pitch/flapping coupling. The essence of the mechanism is that the pitch angle of each blade depends uniquely, and in the simplest case linearly, upon the sum of two terms being constant multiples of the flapping angle of the blade itself and that of the preceding blade respectively.

This definition, although it fully characterises the adopted mechanism, does not represent the most general expression of the fundamental requirements. This must be expressed in terms of the following magnitudes :—

1. Ratio between maximum amplitudes of pitch variation and flapping oscillation—d.
2. Non-dimensional blade inertia about flapping hinge expressed by J/K.
3. The azimuth angle (α) between the phase of maximum flapping and the phases of maximum pitch amplitudes of any blade moving through a revolution. This phase difference can be registered in a variety of ways, none of which is a direct materialisation of its fundamental definition since, of course, no blade can be in two places at the same time. In reality the phase displacement can be introduced in one of the following ways :—
   (*a*) By making use of a neighbouring blade.
   (*b*) By introducing a datum expressing the steady motion of all blades.

(*a*) was the method actually used, of which only the mechanical design is new. The idea of coupling between neighbouring blades was first conceived by Oemichen and a combination between such interconnection and a direct pitch change linkage was already mentioned by Young, though in an apposite sense and without realising its limitations.

Method (*b*) has not been previously proposed or used.

Although the two methods are equivalent in fulfilling the basic requirement of phasing, they are different in their response to motions involving higher harmonics of flapping than the first.

The fundamental requirement refers to specific elementary motions of the rotor. It is fortunate that the two basic types of rotor motion, namely tilting and translational motion, do not lead to contradictory requirements and tilting motion can be taken as the determining condition,

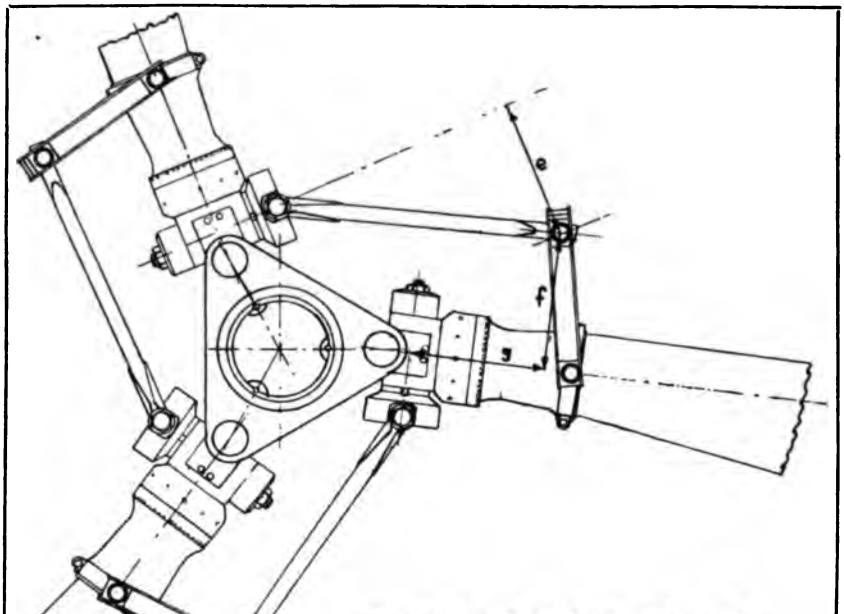
being much easier to handle analytically in view of the absence of inherent second harmonics of flapping.

We can now express the fundamental requirements in the following form :—

$$\tan \alpha + \frac{I}{d}\frac{I}{\cos\alpha} = 2\frac{J}{K}$$

It can be easily verified that for any reasonable values of J/K and a value of d around 2, the fundamental requirement cannot be fulfilled by either a direct pitch/flapping linkage or a pure " backed coupled " linkage and must, therefore, be met by a compound linkage except in a six-bladed fotor where a pure " back coupled " linkage is possible.

Leaving the generalised expression we concentrate on the actual mechanism incorporated in the W.9 rotor. A drawing shows the mechanism. The essential dimensions of this drawing are e, g and f; their effective



COMPOUND BACK COUPLING LINKAGE

ratios are — $p = g/f$, $q = c/f$, referred to as the direct and advanced pitch change ratios. These two form the coefficients in the expression for the blade pitch, where θ_2 is the representative geometric pitch of blade No. 2. θ_0 is the pitch setting at zero coning. β_2 the flapping angle of blade No. 2., β_1 the flapping angle of the preceding blade No. 1.

$$\theta_2 = \theta_0 - p\beta_2 - q\beta.$$

To characterise this rotor system quantitatively, the most significant

built-in geometry parameters are the following combinations of the above ratios p and q :—

1. The coning ratio $k_c = p + q$.
2. The advance proportion $s = \frac{q}{p}$

The coning ratio is important on its own as it determines the behaviour of the rotor in all symmetrical flight conditions such as vertical climb and descent, and, in this respect, is the equivalent to the pitch change ratio in a simple linkage.

However, the operationally significant magnitudes are the ratio d_E of maximum effective pitch variation to the maximum flapping amplitude and the angle α_E between the phase of maximum flapping and the phase of maximum effective pitch variation. Effective pitch is the sum of geometric pitch and the first harmonic of flapping, which sum, in conjunction with a given slip stream velocity, determines the incidence and hence lift of the blade. These operational parameters can be expressed in terms of geometry parameters.

The importance of d_E and α_E derives from the fact that they are simply connected with the magnitude of flapping c_o during a steady rate of tilt and with the azimuth angle ψ_o between the phase of maximum flapping amplitude and the normal to the axis of tilt.

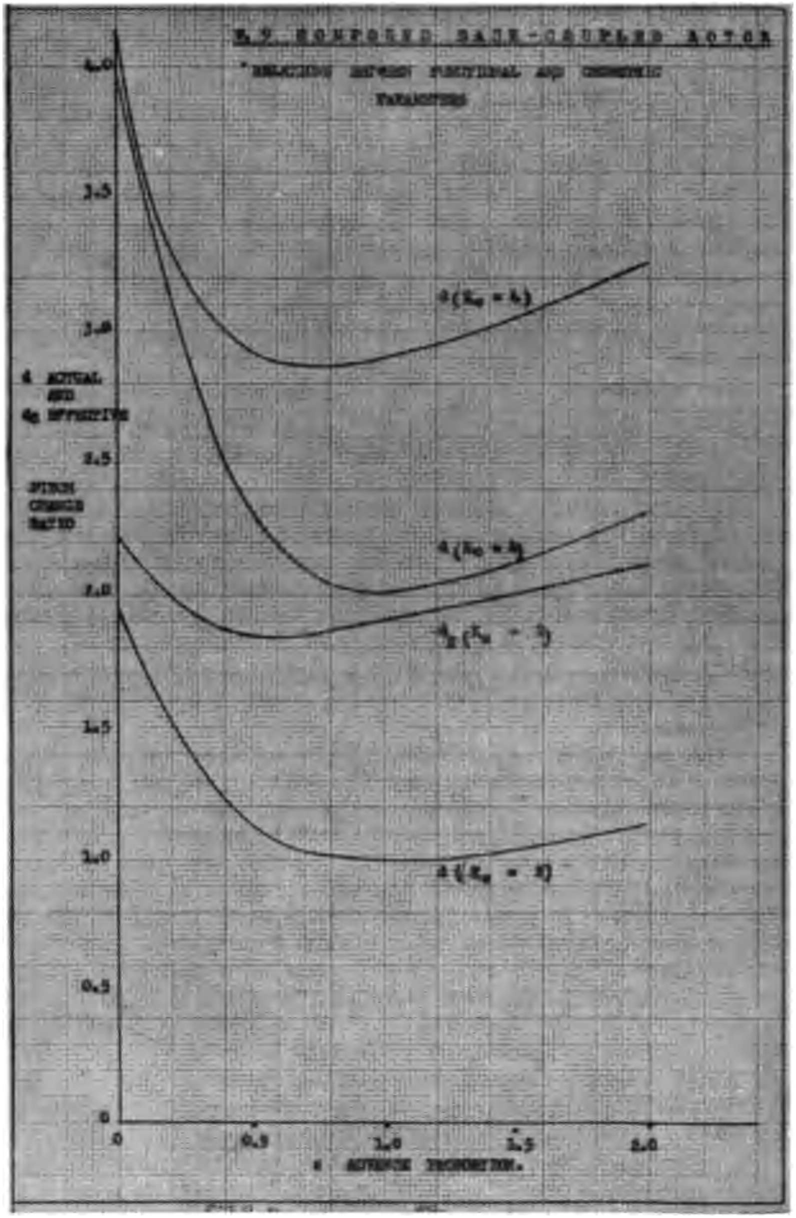
In numerical terms relations are given in graph form which is self-explanatory. It is seen that with coning ratios k_c between two and four, the advance proportion to achieve flapping in phase with the normal to the axis of tilt ($\psi_o = 0$) is around unity and this advance proportion was actually adopted in the W.9 machine whilst the coning ratio was maintained at 2. A graph shows d_E as a function of p for equal k_c.

It is to be noted that numerical relations are not greatly affected by flapping hinge off-set and its elimination means a great simplification in the formulae.

Blade flapping motion in forward flight was investigated by setting up equations of motion incorporating the two first harmonics of flapping and solving 5 simultaneous differential equations for various advance proportions to obtain the unknown flapping coefficients. Calculations were carried out for a coning ratio of two and the results are presented showing the maximum amplitudes of first and second harmonics of flapping C_1 and C_2, the tangent of the out of phase azimuth angle b_1/a_1, and the coning angle as, at a tip speed ratio of $M = .35$ and a through-flow ratio λ corresponding approximately to level flight with a given forward drag. It is seen that the maximum amplitudes of flapping vary but little over the whole range of advance proportions but the phase angle alters considerably, going through zero around an advance proportion of unity.

These investigations also show that with a coning ratio of zero, there is some out of phase component of flapping which can be eliminated by introducing a direct pitch/flapping coupling of .4.

The behaviour of a machine equipped with a compound back coupling linkage in regard to performance, control and hovering stability has already been referred to under the appropriate headings. Summarising, the *elimination* of out of phase components of flapping leads to a behaviour as


4.0
3.5
3.0
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2.0
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1.5
2.0

predicted in a machine in which the out of phase component is *disregarded*, provided d_E has the same value. On the basis of equal coning ratio, the compound linkage is slightly more effective. In performance computations it is presumed that the coning ratio alone is of any consequence and influences r.p.m. requirements at a given setting angle throughout the forward speed range.

When the W.9 machine was equipped with the compound linkage, it became at once controllable in hovering and it must be concluded, therefore, that out of phase components of flapping approaching in magnitude the in-phase components during the application of control are unacceptable to the helicopter pilot and make it impossible for him to control the machine.

Several hours of flying were logged with this set up in its final form, incorporating several adjustments of lever ratios, etc. Anticipating further findings, it can be said broadly that " azimuth " control was successful and, after some adjustments, could be considered as equivalent to the Sikorsky R.4 machine in flying qualities.

The above account is necessarily incomplete, but it is believed that the selected topics represent those aspects of the many phases of W.9 development which are of general interest from the technical point of view.

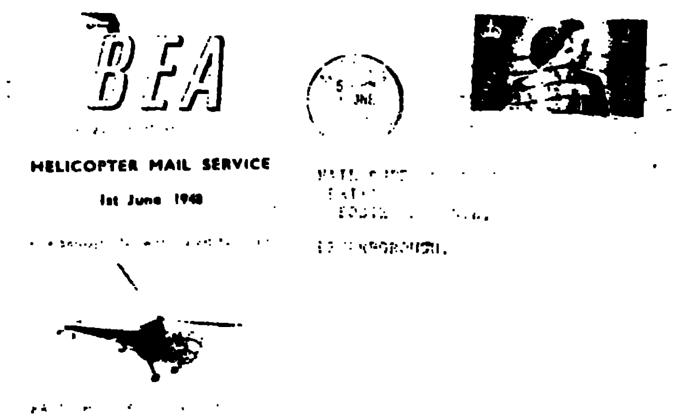
It has been said that experience consists in learning from other people's mistakes. The Cierva Autogiro Co., it's Chief Designer, Mr. C. G. Pullin, and my colleagues had to learn from their own mistakes. In view of the record of the Company and it's associates in the development of Rotating Wing Aircraft, they can afford to be candid in the assessment of past experience true to the motto of Francis Bacon : " Truth emerges more easily from error than from confusion." It is this spirit which enables us to look confidently into the future and await the unfolding of subsequent developments representing the materialisation of years of experience in practical machines for practical users.

References from which general information has been extracted are too numerous to be listed. I have to acknowledge gratefully the help of my colleagues on the Staff of the Cierva Autogiro Co., and wish to express my appreciation of the company's permission to disclose the information given in this paper. It gives me particular pleasure to acknowledge the continued support given to our work by the Ministry of Supply and, in particular, by Captain R. N. Liptrot, D.D.R.D. Helicopters. I thank you, Ladies and Gentlemen, for being a patient and attentive audience.

HELICOPTER WORLD SPEED RECORD COMES TO GREAT BRITAIN *

Flying the Fairey Gyrodyne, over a 3 kilometre stretch on the railway line near Maidenhead on June 28th, 1948, Basil Arkell, Helicopter Test Pilot for Fairey Aviation Company and a Council Member of this Association, broke the world speed record, previously held in America by the Sikorsky S.51 at 114.6 m.p.h., by practically 10 m.p.h. when he achieved a speed of 124.3 m.p.h., averaged over two runs in each direction.

Mr. H. R. Horrell, Deputy Mayor of Peterborough, handing the Royal Air Mail pennant to John Theilman, B.E.A. Helicopter pilot, prior to take off. On the extreme left is W/Cdr. R.A.C. Brie, official in charge of the B.E.A. Helicopter Unit.



On 1st June, 1948, the Helicopter Unit of the B.E.A. inaugurated an experimental Helicopter Air Mail Service between Peterborough, Norwich and Great Yarmouth. Pilot J. Theilman flew the first "live mails" from Westwood Aerodrome after a formal ceremony at which Mr. E. B. Davies, Midland Regional Director, G.P.O., and Councillor H. R. Horrell, Peterborough's Deputy Mayor, had wished the unit luck with this most important experiment. Above we reproduce a commemoration letter cover flown in the helicopter after the ceremony.

*** Subject to homologation by the F.A.I.**

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Editorial

The first open air meeting of the Association was held on Saturday July 10th, at Heston Aerodrome. Although hitherto no programme has been arranged during the summer months, the popularity of such gatherings seems assured. Unfortunately it was not possible to make the arrangements on any other date and considering the unavoidable clash with the Gatwick Air Display, the attendance of over 150 members and guests reflects the keenness of the Association on this type of meeting.

We wish to record our thanks to The Fairey Aviation Company for the courtesy shown in extending this first invitation.

Following the paper read by Dr. J. A. J. Bennett on the Gyrodyne, which is reproduced in this issue, a short film was shown which included some of the early flight trials and later shots of the machine flying over the record course at White Waltham. There followed an excellent tea party in the Control tower restaurant and the meeting concluded with a flight demonstration of the Gyrodyne. In this respect another precedent was created. It was obviously impossible to arrange for members to fly in the machine, but an exception was made in the case of our Chairman who promptly accepted the Fairey Company's invitation to fly, and thus became the first passenger outside the Company's staff to fly in the Gyrodyne.

It is to be hoped that in subsequent years, further similar meetings can be arranged to give practical demonstrations of the various types of helicopters at present being developed in this country.

The Association is also looking into the possibilities of organising an Anglo-American, or International, Forum and Flying Meeting and a sub-committee has been formed for this purpose. While it seems unlikely at present that the organisation will be sufficiently far advanced to be able to hold such a meeting next year, the response and keenness which has so far greeted the sub-committee's activities is such that we feel there will be no lack of participants when the organisation is developed.

M. J. B. Stoker—an appreciation

Most members will be aware that Mr. M. J. B. Stoker—or " Max " as he is affectionately known—has been Hon. Secretary of our Association for the past 18 months, but perhaps it is not so well known that he has recently resigned and handed over the Honorary Secretaryship to Major J. W. Richardson.

Max first became associated with rotary wings in 1933 when he learnt to fly at the Autogiro Flying School at Hanworth, having previously been in business in South Africa for some years. During the latter part of the 1914/18 war he was an observer in the R.F.C. and was mentioned in despatches, so it will be seen that flying was not entirely new to him. Having taken his ' A ' Licence in March, 1943, he continued flying autogiros and qualified for a ' B ' Licence and Instructor's Certificate, being eventually employed by the School as an Instructor until the out-break of the last war. He immediately volunteered for the R.A.F. and was accepted in the Special Duties Branch for Intelligence work. This work continued until April, 1940, when he was given the job of organising a small autogiro flight at Odiham. A number of pilots were converted for autogiro flying with this flight, and it was amalgamated after a few months with another rotary wing unit at Duxford under the command of Squardon Leader (later Wing Commander) R. A. C. Brie, and Max returned to the Intelligence Branch at the Air Ministry. It is interesting to note that he was one of the very few pilots flying during the war who had no visible means of support, *i.e.*, a flying brevet or wings, and also that all his flying, which represents some hundreds of hours in total, was carried out on autogiros, and he has never flown a fixed wing aircraft solo. He continued with his Intelligence Duties right through to the end of the war and was decorated by the Norwegian and Dutch Governments for his work.

On release from the R.A.F. he took an appointment with the Ministry of Labour.

He became a Founder Member of our Association and very early on was asked to serve on the Publications Committee. Early in 1947 he was also asked to take the post of Hon. Secretary and carry on the good work started by Squadron Leader Arkell, and has been serving in both capacities until recently.

His plans for going back to South Africa have been maturing for some time, and he has now returned to settle down and start business on his own account.

Anyone who has known Mr. Stoker will agree that he is a person of sterling worth, and it has always been a pleasure and privilege to work with him. He has done an excellent job of work for the Association and as a mark of appreciation, the Council, on behalf of all Members, recently presented him with a silver ash tray suitably inscribed. A very enjoyable private farewell party took place the night before he sailed.

In conclusion I am quite sure that Max carries with him the best wishes *of all our* Members for his health and prosperity in his new sphere of life.

FOURTH LECTURE 1948

The Fairey Gyrodyne

By J. A. J. BENNETT, D.Sc., F.R.Ae.S.

A lecture presented to The Helicopter Association of Great Britain on Saturday, July 10th, 1948, at Heston Aerodrome, Middlesex.

H. A. MARSH, A.F.C.,A.F.R.Ae.S., IN THE CHAIR

Introduction by the Chairman.

HESTON, SATURDAY, 10TH JULY, 1948.

Ladies and Gentlemen,

I am sure you will agree that it is quite unnecessary for me to introduce DR. BENNETT formally. He has previously lectured before the Helicopter Association, to say nothing of numerous lectures to learned Societies both at home and abroad. I also feel quite certain that most of you are familiar with his background in the rotary wing field of aviation.

On behalf of all Association Members and their guests, I should like to thank the Directors of the Fairey Aviation Company for their kindness and hospitality to us today, and also thank those members of the Fairey Company Helicopter Division whose work has made this visit possible.

Finally, on behalf of the Association, may I congratulate the Fairey Aviation Company again, together with all those responsible, for the excellent show in their recent successful attempt to raise the Helicopter world speed record. Personally, I feel that given the right conditions they are quite capable of increasing this record still further.

Dr. J. A. J. Bennett.

MR. CHAIRMAN, LADIES AND GENTLEMEN : I should like to say on behalf of my colleagues of the Fairey Aviation Co. and myself that it is both a pleasure and an honour to have you here this afternoon, especially as this is the first meeting of the Association at which a helicopter has been available for demonstration. It is perhaps appropriate that this helicopter is one of

British configuration and construction, and in fact is the only one existing in which also a British power unit is installed. I should mention at the outset that full credit should be given to the Fairey Company for their firm belief in the gyrodyne principle from the beginning and for having sufficient faith in their own judgment to sponsor it entirely as a private venture.

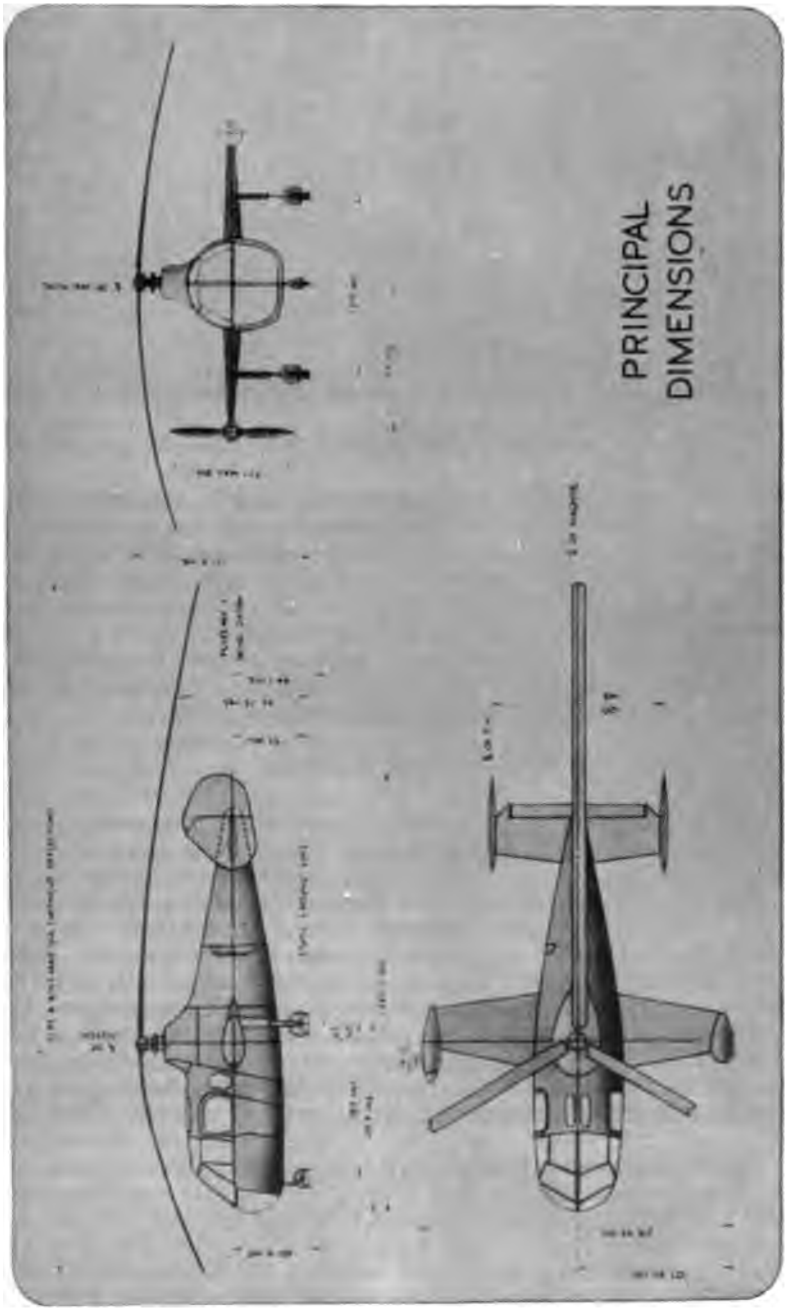
The conception of the gyrodyne originated in this country shortly before the War, to fulfil a Naval requirement for a rotary-wing aircraft capable of operating from the deck of a ship. It is true that the possibilities of the gyrodyne gained immediate recognition by the award of a contract from the Air Ministry, but the War intervened and it was not untill 1946 that the development of the gyrodyne really commenced. During the intervening period the helicopter became a fully-fledged flying machine incorporating certain features of the gyrodyne, *viz.*, the aerodynamic asymmetry of a single lifting rotor in torque balance with a single non-lifting airscrew, the variation of power distribution between branch transmission systems, and lastly the direct control from foot pedals of the collective pitch of the non-lifting airscrew for effecting control of the aircraft in yaw. All of these gyrodyne features have become standard practice in helicopter design.

Where the gyrodyne differs in principle from the standard form of helicopter is in the azimuth location of the non-lifting airscrew. At first sight this might appear to be a matter of minor importance, any position in azimuth from zero to 360° being as good as any other, the choice being determined merely by a desire to mount the non-lifting airscrew as far as possible from the axis of the lifting rotor, thereby keeping the power absorbed by the non-lifting airscrew at a minimum, and the power applied to the lifting rotor at a maximum. The gyrodyne, on the contrary, aims at keeping the rotor power as low as possible and utilises the remainder for the useful purpose of forward propulsion. Although part of this remainder is used normally for torque balance in hovering flight, the whole of the remainder is available always as a reserve for vertical climb under abnormal circumstances. A slow rotation of the fuselage in vertical climb can effect a considerable change in power distribution between the propeller and the rotor. Consequently, vertical climb can be temporarily boosted whenever necessary.

What is a " Gyrodyne "

According to the British Standard Glossary of Aeronautical Terms, aircraft are classified into two separate categories, " aerodynes " and " aerostats," an aerodyne being a heavier-than-air aircraft. A gyrodyne, therefore, is a kind of gyratory aerodyne. In other words, a gyrodyne is a form of helicopter in which the rotating wings are basically the sole means of sustentation but not necessarily of propulsion, the main objective being to keep the power transmitted to the rotor as low as possible and thereby provide greater safety in operation. It so happens that the steps taken in the design of this form of helicopter to enhance its safety result also in a higher top speed, though speed is considered of secondary importance to safety. The higher the forward speed, the less proportion of the total power is delivered to the rotor. Hence the main transmission is not so highly stressed at top speed as at slower speeds, thus ensuring a higher factor of safety.

A further safety feature of the present gyrodyne is its low-pitch operation under all conditions of flight and, with its relatively low disc loading, it



Association of Gt. Britain.

Early flight trials at Heston.

possesses well-proven qualities of the gyroplane which the helicopter should seek to retain. It is regrettable that present-day helicopters should have sacrificed safety to such a degree that the Parliamentary Secretary of the Ministry of Civil Aviation was obliged recently to refer to the matter in the House of Commons. While we do not entirely agree with the statement made on that occasion, the high-pitch operation of helicopters is a definite source of danger, but it should not be assumed that all helicopters are necessarily dangerous. The gyrodyne, by keeping rotor power, disc loading and pitch as low as possible, increases the margin of safety.

The Gyrodyne Principle.

Attempts have been made in the past to discover a method of propulsion for helicopters so that the tip-path plane should remain horizontal in level flight. Probably the nearest approach to the gyrodyne was an arrangement described by OEHMICHEN in which translational flight was effected by differential variation of the thrust of a group of propellers. The use of a single propeller was discarded, however, because the machine would be unable to hover owing to the unbalanced thrust of the propeller. The gyrodyne does not attempt to keep the tip-path plane horizontal under all conditions of flight, nor to maintain constant power distribution between rotor and propeller. The single outboard propeller maintains torque balance, not only with varying rotor torque, but at zero forward speed, in which case the tip-path plane is inclined backwards so that the forward thrust of the propeller is balanced by the backward component of the rotor thrust.

Translational speed is achieved by decreasing this backward inclination of the tip-path plane and not until a fairly high forward speed has been attained does the tip-path plane assume a horizontal attitude. Beyond this forward speed, of course, the tip-path plane has a slight forward inclination. In other words, the normal operating condition of the gyrodyne is with both the fuselage and the tip-path plane substantially level.

Periodic blade-tip stall.

At one time it was thought that the better propulsive efficiency of a driven sustaining rotor compared with that of a propeller would result in a higher top speed for the helicopter than for the gyroplane. In this respect the helicopter has not come up to expectations. A bugbear of the helicopter, affecting its propulsive efficiency in forward flight, has been the periodic blade-tip stall. This shortcoming is minimised in the gyrodyne.

Perhaps this point is best explained by considering the axial component of flow through the rotor disc, *i.e.*, the flow of air in a direction perpendicular to the tip-path plane. The autorotative rotor of the gyroplane is inclined at a positive angle of incidence with respect to the flight path and the rotor is kept rotating by the axial component of flow which, in this case, is directed upward relatively to the tip-path plane. A change in axial flow does not alter the blade angle of attack equally from root to tip, but affects the root portion of the blade most. Hence, an increase in axial flow merely extends the periodic stall at the blade root and the operation of the rotor remains fairly smooth, though, of course, if too great a proportion of the blade becomes stalled, the vibration from the rotor may be excessive.

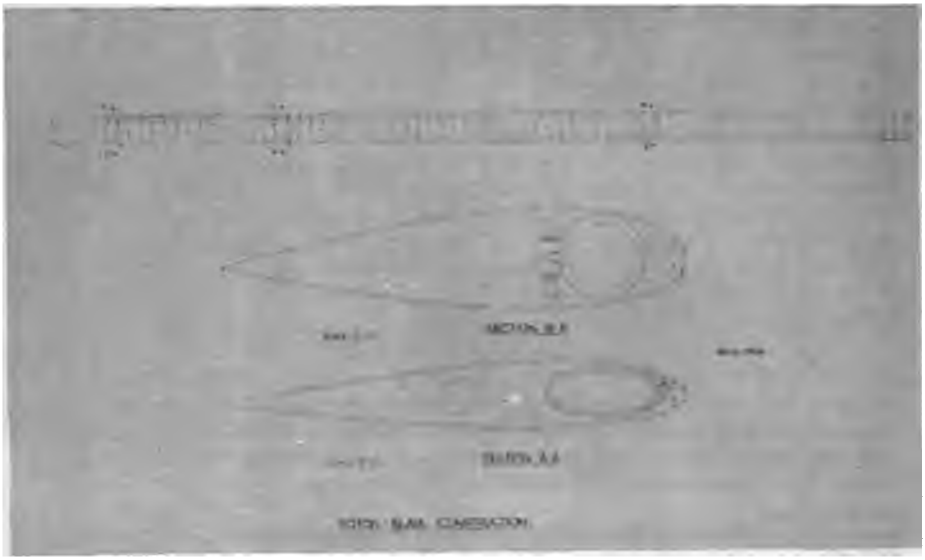
Basic Limitation of Forwardly-Inclined Rotor.

The periodic blade-root stall of the autorotative rotor, however, is relatively innocuous in comparison with the blade-tip stall occurring when the rotor thrust of the helicopter is inclined forwardly for propulsion. The rotor disc then makes a negative angle of incidence with respect to the flight path, as a result of which the axial flow through the rotor increases with forward speed. To compensate for the reduced angle of attack caused by the increased axial flow, the blade angle has to be increased and at a high forward speed it is generally greater than the maximum value at which the rotor would autorotate in power-off flight. Hence, in the event of power failure the blade angle must be quickly decreased to prevent the blades from losing their kinetic energy and stalling, though, on the other hand, a sudden large reduction in pitch may be extremely dangerous.

The effect of the increased axial flow on smoothness of operation of the rotor is more marked than in the gyroplane because, in the helicopter with the rotor forwardly inclined, the axial flow is downward and an increase in axial flow affects the tip portion of the blade least. Consequently, when the mean collective pitch is increased to compensate for the increased axial flow, the blade angle at the tip is excessive and the blade tip approaches the stall cyclically at high translational speeds, especially as the angle of attack on the retreating blade is already high due to blade flapping or cyclic feathering resulting from the aerodynamic dissymmetry of forward flight. The helicopter rotor, therefore, becomes rough in operation at high pitch in forward flight, though it may be quite smooth at the same forward speed in auto-rotative flight.

Advantages of low pitch.

It may be argued that there is no need for the helicopter to travel fast ; there are plenty of uses awaiting slow-speed machines for some time to come. But even if one neglects the possibilities of increased speed offered by the gyrodyne principle, the smoothness associated with low-pitch operation is in itself a desirable attribute. It is unnecessary to exceed the maximum



autorotative blade angle to compensate for an increased axial flow resulting from a forward inclination of the rotor. In other words, the propulsive powered-rotor departs too far from the satisfactory condition of operation of the autorotative rotor, and the relatively non-propulsive powered-rotor of the gyrodyne avoids the limitations of the two extremes.

Automatic pitch variation.

Apart from the novelty of the gyrodyne configuration, the Fairey prototype incorporates a number of novel features, with regard to which patents are pending in a number of countries. Blade torsional bearings are eliminated entirely, and collective pitch change is effected automatically about the flapping and drag articulations. There are no flight controls other than stick, throttle and foot pedals. At the request of the Ministry of Supply, however, an alternative hub arrangement has been designed incorporating an over-riding collective-pitch control mainly for trim purposes at altitude and this will be evaluated later under a Government contract.

Tilting-head control.

The present machine is controlled by a tilting-head arrangement which eliminates the multiple levers and bearings of the conventional cyclic-pitch method, although the alternative hub for the Ministry of Supply is provided with cyclic-pitch as well as collective-pitch control. It should be of interest to compare the operation of the two alternative systems on the same aircraft.

Cyclic-pitch control has so far been preferred for helicopters, and control by tilting of the hub axis for rotors which are autorotative in flight, mainly for reasons of mechanical simplicity in either case, but also in the case of the helicopter because cyclic-pitch control allows the tip-path plane to remain nearly perpendicular to the hub axis, which is important for the *purpose* of minimising vibration. As the gyrodyne rotor normally operates

neither in the non-powered condition of the autorotative rotor nor in the fully-powered condition of the propulsive rotor, but somewhere about half-way between these two extremes, it is appropriate that the control should conform to neither of the two conventional forms but should combine certain features of both. It resembles the tilting-hub method, but in the gyrodyne the hub axis, *i.e.*, the axis of the main bearings, is not tilted. Instead, the rotor head—the hub member to which the blades are attached—is tilted with respect to the hub axis, and in forward flight the forward inclination of the head balances the backward inclination of the tip-path plane with respect to the head so that the tip-path plane remains substantially at right angles to the hub axis, giving effectively the same result as cyclic-pitch control.

The three flapping hinges all intersect on the axis of rotation and are inclined to the blade axes at about 60° when operating at zero torque. In response to torque, this angle increases progressively and attains a value of about 70° at full torque. The automatic change in blade angle is associated with the angular displacement of the blade in azimuth and is caused partly by a so-called " alpha one " inclination of the drag hinge and partly by the variation in " delta three." The combined effect is such that there is an immediate increase in boost whenever the throttle is opened without there being any appreciable change in angular speed of the rotor. The blade articulations, therefore, self-govern the collective pitch quite independently of any over-riding collective-pitch control that may eventually be provided for other purposes.

Rotor Head

Rotor Blades.

The rotor blades are of steel tubular spar and wooden rib construction are covered with plywood and fabric. The spar is circular in section root end, but, over the greater part of its length, it is of oval section, h combines rigidity in torsion with flexibility in vertical bending. ot flange integral with the spar enables the blade to be attached to the fitting without perforation of the tube with its attendant stress concentra- Drilling of the spar is avoided also at the rib clips which are

Power plant installation

attached frictionally over the main portion of the blade and not by bolted or welded joints. The rotor blades have been manufactured to very close tolerances and, as a result, have been trouble-free throughout all the tests. The hydraulic dampers for damping the blade motion in the plane of rotation, although provided with only a moderate amount of damping, have proved satisfactory in suppressing entirely self-excited instability.

Other design features.

The present fuselage is of steel tube construction although a metal monocoque fuselage is being provided for production. The pilot's seat is

Power Plant and Transmission System.

The Fairey prototype is powered by an Alvis " Leonides " 9-cylinder, air-cooled radial engine which has a maximum sea-level rating of 515 b.h.p. at 3,000 r.p.m. It is mounted vertically inside the fuselage and cooled by a fan driven at engine speed. The cooling air is drawn in through openings in front of the rotor pylon and discharged through ducts in the tail unit. Ducts are also provided to deflect air through the oil cooler and the engine-driven generator.

The installation of the power plant and transmission consists of four self-contained units ; first, the engine, its mounting and cooling system ; second, the main gearbox providing the first stage reduction gears for the rotor and propeller drives, and incorporating the clutch and the freewheel ; third, the top gear-box housing a double epicyclic gear which provides the final gear reduction between the engine and the rotor, with a rotor brake mounted above it ; and fourth, at the outer extremity of the starboard wing, a gear-box carrying the propeller reduction and pitch-changing gear.

The engine is coupled to the main gear-box by a splined shaft carrying a multi-bush universal coupling at each end, the fan being mounted on to the coupling nearer the engine. This arrangement allows the engine and fan to float on the rubber mountings provided for the engine and covers mal-alignment between the engine and the main gear-box.

Main Gear-Box.

The main gear-box which is mounted on four rubber bushes, carries the clutch, the vertical shaft drive, the side propeller drive, the freewheel, the Lockheed pump drive, the oil pump for the main and top gear-boxes and the engine and rotor tachometer drives. The propeller is positively geared to the engine and is unaffected by clutch operation. The vertical shaft is driven by bevel gears and the propeller by a smaller pair of bevels. A central shaft running at engine speed carries the clutch casing and the clutch plates are splined to an extension on the driving bevel. A " Lucas " actuator is provided for controlling the rate of clutch engagement, thus limiting the maximum starting torque and ensuring that the rotor blades can not be damaged by a sudden engagement of the clutch. The freewheel is located above the main bevel and, to ensure that the rotor tachometer and hydraulic pump are driven when the rotor is freewheeling, the drives for these services are located above the freewheel.

Top Gear-Box.

The top gear-box is coupled to the main gear-box by a tubular vertical shaft fitted with a torsional rubber coupling at each end. Oil is delivered to the top gear-box by a pump located in the oil sump of the main gear-box and circulates through the top gearing, the freewheel and the gearing in the main gear-box, before returning to the sump. Thermocouples are fitted to all gear-boxes. The oil cooler is carried in a duct which diverts air from the fan through the cooler.

Propeller drive.

The propeller shaft, which is in two lengths, is driven from the main gear-box through a torsional rubber coupling embodying a sliding joint. A rubber-mounted bearing is located at the centre of the propeller shaft to support the " Hardy Spicer " universal coupling which connects the two lengths of shaft. A second " Hardy Spicer " coupling connects the outboard end of the shaft to the propeller gear-box. This gear-box carries its own oil pump and oil supply.

Rotor Blades.

The rotor blades are of steel tubular spar and wooden rib construction and are covered with plywood and fabric. The spar is circular in section at the root end, but, over the greater part of its length, it is of oval section, which combines rigidity in torsion with flexibility in vertical bending. A root flange integral with the spar enables the blade to be attached to the root fitting without perforation of the tube with its attendant stress concentration. Drilling of the spar is avoided also at the rib clips which are

Power plant installation

attached frictionally over the main portion of the blade and not by bolted or welded joints. The rotor blades have been manufactured to very close tolerances and, as a result, have been trouble-free throughout all the tests. The hydraulic dampers for damping the blade motion in the plane of rotation, although provided with only a moderate amount of damping, have proved satisfactory in suppressing entirely self-excited instability.

Other design features.

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Photo: Charles E. Brown

Great Britain establishes new International Helicopter Speed Record.

The Fairey Gyrodyne, piloted by Basil Arkell, on a 3 kilometre course at White Waltham, over which the new speed record of 124·3 miles per hour was established.

on the port side at the nose end of the cabin and to his right an occasional seat with dual control may be installed. The back seat is designed to take three passengers. The rear portion of the fuselage carries a tailplane and outboard fins which are required for stability purposes in forward flight. The stub wings are merely fairings for the structure supporting the outboard propeller and the main legs of the tricycle undercarriage.

The flight controls are, as in the conventional aeroplane, stick, throttle and foot pedals. The stick controls the angular displacement of the head through hydraulic jacks, which completely eliminate stick shake, though the initial few hours of flight were performed with reversible controls. The operation of the collective pitch of the propeller by the foot pedals is also arranged hydraulically. Centralising springs are provided in all controls.

Performance.

The flight trials of the prototype are being conducted at a gross weight equal to that of the production aircraft, which including pilot, 3 passengers, 150 lbs. luggage and 47 gallons of fuel, is approximately 4,800 lbs. The empty weight of 3,600 lbs. is apportioned as follows :—

Rotor blades	8%
Power plant and transmission	47%
Structure	30%
Fixed equipment	15%

The rotor diameter being 52 ft., the corresponding disc loading is 2.25 and as the solidity is relatively low, being only 1% per blade, the blade loading has a relatively high value of 75.0. At 3,000 engine r.p.m. the rotor speed is 227 r.p.m., giving a tip speed of 619 ft./sec. and a thrust coefficient of 0.082 (based on blade loading).

The first flight of the gyrodyne entirely free from ground restrictions was accomplished successfully on December 7, 1947, after a period of preliminary ground testing, during which the engine was run for 85 hours and the rotor for 56 hours. At 4,800 lbs. gross weight and 190 rotor h.p. the blades have sustained in hovering flight at a few feet from the ground a load of 25 lbs. per rotor h.p. which allows an ample margin of power for vertical climb even assuming that the power applied at the rotor hub is only 50% of the brake horse-power developed. The present gyrodyne therefore, differs, little in vertical performance from the best existing helicopter and, without making any definite claim at this stage in regard to climb (at the best climbing speed) and in regard to maximum speed in level flight, the gyrodyne appears in both respects to be markedly superior to present helicopters. Moreover, this improvement in performance is effected without departing appreciably from the low disc loading and low pitch advantages which contributed basically to the remarkable record of safety achieved by rotary-wing aircraft in the pre-war era.

Mr. O. L. L. Fitzwilliams' Vote of Thanks to Dr. Bennett.

Mr. Chairman, Ladies and Gentlemen,

I have accepted with pleasure our Chairman's invitation to propose a vote of thanks to Dr. Bennett and, to start with, I would call your attention to the large attendance at this lecture. In view of today's counter attractions at Gatwick this excellent turn-out is both an encouraging sign of the keenness of the Association's members and a tribute to the high regard we all have for Dr. Bennett.

I would also like to add my congratulations on the Gyrodyne's successful establishment of a new speed record. For passenger operation there is no doubt that high cruising speed is becoming an increasingly important aim in helicopter design, but in spite of the Gyrodyne's success we have little cause for complacency. Indeed it is curious to reflect that whereas today we have a helicopter speed record standing at 124 m.p.h., some 13 years ago the Pitcairn PCA-2 was being flight tested at speeds up to 160 m.p.h. and at tip speed ratios far in excess of any employed today. Certainly this speed was registered in dives but it is well beyond the permissible diving speed of most present-day helicopters ; moreover the tip speed ratios achieved would today correspond to a speed of the order of 200 m.p.h.

The Gyrodyne configuration therefore demands the most careful attention, not only because of its many interesting technical features but also because it represents the considered judgment of the man who is our chief link with the very extensive experience accumulated in the development and operation of the Cierva Autogiros. I believe that, for future designs, there are a number of important lessons to be learned from the Gyrodyne and it progress will certainly be followed with the greatest interest.

For instance, the use of auxiliary airscrews for horizontal propulsion is of course by no means a novelty in the design of helicopters but the Gyrodyne calls our attention to this arrangement in a manner and at a time which is of peculiar significance since we are now approaching the 150 m.p.h. or so speed beyond which horizontal propulsion by tilting the main rotor is not expected to be practicable. However, helicopter speeds (and especially cruising speeds) are likely to remain well below this figure for some time to come and it would therefore be most unwise to jump to the conclusion that there is at present anything wrong with the many other single and multi-rotor projects which obtain their forward propulsion by tilting the main rotors.

In respect of safety too I feel that Dr. Bennett would be the first to agree that the attention which he has drawn to this aspect of the Gyrodyne's performance should be understood not as a reflection on other helicopter configurations but as an indication of the degree of safety which is obtainable with rotary-wing aircraft in general. In the course of his lecture Dr. Bennett recalled the statement, recently made in Parliament, that helicopters are not as yet considered sufficiently safe for passenger services and, as we have with us today a number of eminent representatives of the Aeronautical Press, I feel it is only proper, on behalf of all of us who are connected with helicopter development, to register our disagreement with that statement.

So far as I am aware there are no valid reasons for supposing that a helicopter carrying a Certificate of Airworthiness is in any way less safe than a similarly qualified fixed-wing aircraft, whereas the helicopter's flight characteristics are such that there are a number of reasons for supposing the contrary. If some people consider that present-day helicopters are unsafe for the transport of passengers over water or into and out of our large cities, this is not at all because they are helicopters, and even less because they are any particular kind of helicopter, but simply because at present they all happen to be single-engined.

Finally I would like to add my congratulations to the many already received by Dr. Bennett and his colleagues on their considerable technical achievement, and to say that I have the greatest pleasure, on behalf of our Association, in thanking him for his excellent paper and its admirable delivery.

Cierva Memorial Prize

The Council have pleasure in announcing that the Prize for the 1947/48 competition for an essay on " The Safety of Rotary Wing Aircraft " has been awarded to :—

D. R. GARRAWAY, B.SC. (Eng.).

His essay entitled " The Structural Airworthiness of Helicopters with particular reference to Fatigue Failure " is re-produced in this Journal.

Since no award was made for the 1946/47 competition due to the somewhat poor response, MR. GARRAWAY is the first winner of this Prize. The response to the 1947/48 competition was again not altogether as good as had been expected, and it is hoped that the re-production of this essay will lend encouragement to would-be competitors in subsequent years.

The title for the 1948/49 Essay competition has been broadened to allow the widest possible field of entry, and the prize for 1949 will be awarded to the Competitor submitting the best paper of a technical nature on any subject connected with Rotating Wing Aircraft. Papers of a purely historical or journalistic content will not be egilible, but the subject may be broadly construed to include studies in any related field such as Operational, Administrative, Maintenance, Navigation, Safety, and Economics, as well as the more conventional fields of Aeronautical Science and Engineering.

Full details of the rules governing the 1948/49 Competition may be obtained by writing to the Association's Assistant Secretary at Londonderry House, 19 Park Lane, London, W.1., and competitors should apply for these rules before submitting entries. The following summary is appended for guidance :

The competition is not restricted to members of the Association nor is there any restriction as to nationality. Competitors should be under the age of 35 on the 31st December, 1948. Entries for 1948/49 must be received by 31st March, 1949.

Papers should be written preferably in English, but will be accepted in French or German, and are recommended not to exceed 5,000 words. Competitors must state date of birth and be prepared to submit proof of date of birth if called upon to do so. Entries must be typed and submitted in triplicate. Written entries will not be considered. Diagrams of figures accompanying the text must be clearly drawn in Indian ink, and if not in triplicate, must be on tracing paper and capable of reproduction in print.

Entries must be original papers, not previously submitted to any other body and not previously published ; the copyright of the winning paper submitted becomes the property of the Association and no papers will be returned to competitors.

The Structural Airworthiness of Helicopters with particular reference to Fatigue Failure

By D. R. GARRAWAY, B.Sc. (Eng.).

The author is a member of the Association and is on the design staff of the Helicopter Branch of the Fairey Aviation Company. He is 24 years of age and has been associated with rotary wing aircraft for three years.

CIERVA MEMORIAL PRIZE ESSAY, 1947/48.

Summary.

The importance of reliable airworthiness criteria is stressed in an introductory paragraph. Practice in aeroplane design is reviewed briefly, noting particularly the current tendency to permit increasingly severe fatigue loads. The principal loads on the elements of a helicopter are enumerated, and consideration of their repetitive nature leads to an extended discussion of fatigue failure and methods of correlating fatigue loads. Suggestions are offered for a rationale of provisional strength requirements and the amendments desirable following the establishment of additional data. The need in this connection for extensive V-g and blade stress records taken in operation is emphasised.

ESSAY.

Many people in Great Britain are now confident that helicopters will shortly be in general use for a variety of commercial purposes. Some of these anticipated functions are not new to air transport undertakings—certain feeder-line services within the British Isles, for example, may well be operated by helicopters—but the fundamental ability of the helicopter to take-off and land in confined spaces gives it an additional scope in circumstances which preclude the use of fixed-wing aircraft. Many applications in the latter category occur to the mind. Only two of the possibilities are the establishment of passenger and freight services to remote parts of the country, and express mail services between the principal cities. Some districts in Scotland, for example, are at present virtually isolated during part of the year, or can only be reached after a tedious and difficult journey. Little or no preparation would be necessary in arranging landing sites for helicopters. Operational research is already being conducted by the Helicopter Unit recently formed by B.E.A.

Two important facts arise from even the most superficial examination of the field of operations. Firstly, that the successful commercial use of helicopters will depend largely upon the reliability of the machines them-

selves, and secondly, that a high standard of airworthiness will have to be maintained. Operation by relatively unskilled persons—both private owners and commercial employees—and from sites having only meagre maintenance and repair facilities, will demand an exceptional freedom from mechanical troubles. Rotary-wing aircraft cannot be permitted to land freely in the densely populated centres of the principal cities until the safety of such operation has been proved to the regulatory authorities.

The American C.A.A. has already established airworthiness requirements for rotary-wing aircraft. Such requirements, however, have not yet been published in this country. For fixed-wing aircraft, the Air Registration Board's Civil Airworthiness Requirements and the Design Requirements for Military Aeroplanes (A.P.970) of the Air Ministry, cover the field. It is relevant, before considering the problems of helicopter airworthiness, to study briefly certain aspects of the fixed-wing requirements.

The principal fixed-wing loads are specified by a flight envelope, which defines the permissible limiting combination of acceleration and forward speed. The Load-Factor sub-committee of the A.R.C. recommended (1930) that, in general, any manoeuvre which does not leave a factor of safety of 2 on the aircraft structure, during normal execution by a good pilot, should be prohibited. Consideration of acceleration records available at that time led to the specific recommendation of an ultimate load factor of 8. The fatigue effects of manoeuvring loads were thus very slight in a good design, and failure from this cause was likely to occur only once in 10^7 or 10^8 flying hours—a negligible proportion. Since 1930 the increase in aeroplane operating speed and altitude, and in wing-loading, has tended to reduce the manoeuvring load factor. In addition, more accurate methods of stress calculation permit a lower factor of safety. This overall reduction of the maximum normal acceleration factor and the factor of safety, means that the loads imposed by gusts may be critical. The total (ultimate) factor is now specified as 5.25 for aircraft in the normal civil category weighing under 8 tons, and higher for military and aerobatic types.

The frequency of gusts varies with their intensity, the maximum velocity encountered being about 70 ft./sec.—such a case being very rare. If the load imposed on an aircraft structure by a gust of 50 ft./sec. is of the same order as the ultimate load, then that imposed by one of 15 ft./sec.—probably occurring more than a million times during 10,000 hours' flying—may cause fatigue failure during the lift of the aircraft.

These facts, together with the present tendency to increase the flying life of transport aircraft, make it important to take fatigue into account. The P.I.C.A.O. has recommended that " the strength and fabrication of the " aeroplane shall be such as to ensure that the probability of disastrous " fatigue failure of the primary structure under repeated loads anticipated " in operation, is extremely remote during the expected life of the aircraft " or parts thereof. When a type of construction is used for which experience " is not available to show that compliance with static strength requirements " is sufficient to ensure the strength of the structure under repeated loads, " its strength under such loads shall be substantiated by suitable investiga- " tions." Such tests have, in fact, been performed on at least one aircraft, and may be expected in time to become a usual feature in proving the strength of airframes.

The question of rotary-wing aircraft airworthiness may now be studied in the light of aeroplane practice.

The fuselage and landing gear do not present any special problems which cannot be dealt with by established methods. The fuselage loads imposed by manoeuvres are similar to those on fixed-wing aircraft, although at present few data are available upon which to base a normal acceleration factor. The contribution of V-g records in establishing the value of this factor for aeroplanes should not be forgotten. As applied to helicopters the factor has no direct relation with forward speed (V), and it may be considered instead as a function of rotor r.p.m. This is more logical, but the form of the function may vary considerably between different machines, as it is dependent upon the method of control and the governing mechanism if one is fitted. Although it is desirable to record acceleration on a time base, this is difficult under ordinary operating conditions, and the apparatus required is unduly complex. Useful data can, however, be obtained from a standard V-g recorder, which has the merit of separating manoeuvres at zero forward speed. Aircraft fitted with the conventional type of flexible, fully-articulated blades are not very sensitive to gusts, and the maximum acceleration induced in the fuselage does not usually exceed that caused by control operation. An ultimate factor of 3.5 on the normal 1g fuselage loads should be adequate, though this figure should not be employed without investigation unless the design is similar to that of an existing machine of proved airworthiness.

First thoughts may suggest that a light undercarriage is sufficient. Normal power-on landings—a category which may be expected to include nearly all landings during the life of a helicopter—should be treated as a possible cause of fatigue failure, the maximum vertical velocity of such an airborne landing being taken as 4 ft./sec. Power-off landings present a more severe case. The vertical velocity at touch-down may exceed 12 ft./sec. during an emergency, or because of specially adverse conditions. The maximum load developed in these circumstances depends not only upon the characteristics of the helicopter, but to a very great extent upon the pilot's experience and skill in timing. A rational approach to this problem may only be made by the analysis of acceleration records. Until adequate data of this nature are available, attention should be directed to ensuring that failure of the undercarriage will not result in injury to the passengers or crew. Since the forward speed will usually be low during a heavy landing, this condition is not difficult to fulfil.

Unlike the elements so far considered, the rotor has no equivalent in an aeroplane ; but it is unquestionably the most important part of a helicopter. The present discussion will be confined to the most usual type of rotor now in use, namely the hub-driven rotor with flexible, articulated blades. The behaviour of rigidly mounted blades is similar, since they may be replaced as a first approximation by semi-rigid blades having a virtual hinge at some point in the spanwise axis. The chief loads are the centrifugal force, and bending moments in both flapping and drag planes. Shear forces are small, and torsion is not usually critical, except in the case of rotors controlled by ailerons. The centrifugal force is virtually constant, and in most blade designs an ultimate factor of 4 or more may be obtained under this load alone. The presence of a bending moment in the flapping plane is due to the fact that the resultant of the aerodynamic load components in this plane does not pass through the centre of inertia forces. The centre of inertia may be

adjusted by suitable blade design so that it coincides with the aerodynamic centre for a given lift distribution, but in forward flight this latter distribution varies with the position of the blade in azimuth, being concentrated further outboard when the blade is retreating than when it is advancing. It follows that whatever the mass distribution, there will be a cyclic variation of bending moment at each point along the blade. The magnitude of this moment is reduced by blade bending, since the centrifugal force component normal to the blade is modified, and acts as a relief. The inertia forces associated with this bending vibration are comparatively small.

Similar loads occur in the drag plane. The centrifugal force acts at the centre of gravity of the blade ; the distance between this point and the centre of drag is greater than that between the centre of inertia and lift, but since blades are invariably stiffer in the drag plane, the stresses due to bending are of the same order in both directions. Other inertia loads may be present because of a periodic variation of angular velocity and flapping angle. If oscillations in the drag plane are mechanically damped, or resilient hinges employed, the restraint will contribute to the drag moment.

The steady operation of a helicopter in forward flight thus causes, at each point in the load-carrying member, a steady fibre stress and a fluctuating stress. It is usual to state the stress in terms of its maximum and minimum values, by quoting their algerbaic mean and the semi-amplitude of their difference ; that is, in the form $M \pm R$. The constant part of this stress is the sum of the tensile stress due to centrifugal force (which may be as much as $\frac{1}{4}$ of the ultimate stress at some points) and the mean fibre stress due to bending. The frequencies of the principal components of the fluctuating part are once and twice the rotor speed. If the rotor speed is 250 r.p.m. then the first harmonic will complete a million cycles during 70 hours' flight. The fatigue strength of the blade under this combination of loads must thus be studied, rather than the static strength.

The magnitude of the stress at each point depends principally (during unaccelerated flight) upon the forward speed and the rotor speed. Additional loads are imposed by accelerated motion, which may be the result of ground running (take-off, landing and taxying), control operation, or gusts. An understanding of the strength of materials subjected to fatigue loads is necessary before attempting to judge the adequacy of a particular design.

The first experimental studies of fatigue failure were conducted about 80 years ago, and it was soon established—largely owing to the work of Wöhler—that, for example, a steel specimen subjected to reversed bending will fail after a certain number of reversals, that depends on the range of the applied stress. This information is usually presented in the form of a curve connecting the number of reversals (N) at which failure occurs under different values of the stress range (S). In the case of some steels it is found that stresses below a certain limiting value do not cause failure when repeated indefinitely. Fatigue failure of these steels after 20 million reversals is extremely rare, and may be neglected for practical purposes. There is no such fatigue limit for the majority of materials.

The strength of specimens under repeated load is greatly impaired by the presence of irregularities causing stress concentrations, and by poor surface finish. There is not, however, a constant relation between the maximum stress in a specimen caused by, say, a surface notch, and the number of reversals to failure. An improvement in the fatigue life is observed beyond

that which might be expected to correspond to the maximum elastic stress. Improvement is partially due to local work hardening of the material, and depends upon the size and stress distribution of the specimen and upon the structure and elastic properties of the material. Attempts to correlate these effects by a notch sensitivity index (defined as the ratio of the proportional change in fatigue strength of a similar plain specimen compared with the notched specimen, to the proportional increase of elastic stress due to the notch) have not been very successful, the definition itself is unsatisfactory in some respects. An approach along different lines is more encouraging, but it will be sufficient at this stage merely to note that when an estimate of fatigue strength is made from data relating to polished laboratory specimens, an allowance must be included for the stress concentrations and defects of surface finish which occur in practice. Some tests have been performed upon complete structures and structural elements, the fatigue strength of which is commonly found to be less than half that calculated from the nominal stress.

So far consideration has been given only to specimens subjected to equal reversed stress. As in the case of stress concentrations, no general relationship can be found for specimens subjected to a combination of steady and alternating loads, although many investigators have studied the problem. A simple formula can be assumed which leads to conservative results, and is suitable for practical purposes. The " modified Goodman Law " is such a relationship. It is best expressed symbolically :

$$R = R_o (1 - M/U)$$

where $2R_o$ is the safe range of stress at zero mean stress (corresponding, for example, to $\pm R_o$ in reversed bending)

$2R$ is the safe range of stress at mean stress M,

and U is the ultimate strength of the material.

It should be emphasised that this is no more than a convenient rule which, when applied in design, gives a reasonable assurance of safety. Used in conjunction with the S — N curve appropriate to the material in its actual form (*i.e.*, containing stress raisers and surface imperfections) it is evidently possible to derive a value for the permissible range at any given mean stress. That is, the range of load which will not cause failure in less than the specified number of reversals.

It now remains to establish the behaviour of a specimen subjected to a system of loads in which the values of M and R change from time to time. Given a list of loads and the number of cycles corresponding to each, it might be asked whether the specimen will fail. The question cannot be answered directly, except by appeal to a test in which the loading conditions are exactly reproduced. A simple theory has, however, been proposed, which enables problems of this sort to be assessed. The " Cumulative Damage " theory is based on the supposition that each cycle of stress does a certain amount of damage to the material, and failure occurs when the sum of all the damage reaches a critical value. It is commonly observed that when a fatigue test is preceded by a few cycles of overstress the life of the specimen is prolonged, probably because of work hardening of the material. The anomoly—and others—may be removed by modifying the assumptions, but for simplicity these variations will be neglected. Expressed quantitatively, the damage contributed by p_n cycles of stress, under which load alone the specimen has a total fatigue life of c_n cycles, is p_n/c_n. The cumulative

damage under a system of varying loads is then given by the sum of expressions of the type p_n/c_n, each of which represents the effect of a particular load. The material fails, according to this hypothesis, when the sum becomes unity. It follows that the order of application of the loads does not affect the life of the part. Stresses which are less than the limiting stress do not contribute damage, since c_n—the number of cycles to failure—is infinite in such cases. The results of a few tests which have been conducted using a varying load have been checked with the cumulative damage theory. Sufficient agreement is obtained to justify using the theory tentatively, and it is hoped that an extensive investigation will be made shortly, since such a simple method of correlating different loads is an invaluable tool in analysing fatigue effects.

The system of stresses at any particular point in a helicopter blade is very complicated, as has been seen, and must be simplified to make the problem manageable. Consider firstly the steady flight condition ; the aircraft may be expected to spend some part of its total flying life in the state represented by each point within the flight envelope (plot of limiting forward speed versus rotor r.p.m.). If a helicopter spends 1% of 5,000 flying hours in a particular condition, the number of stress cycles completed will be in excess of 500,000. Most of the stresses involved will thus correspond to points on an S—N diagram in the region of which fatigue strength is low and almost constant. Hence load is a more critical factor than the number of reversals. Little will be lost, therefore, by dividing the flying life into a few steady flight conditions corresponding to maximum loads. Such conditions will usually be limiting points on the flight envelope. The cumulative damage due to this system of loads will be not less than that ooccurring in practice.

The alternative is to integrate (over the whole envelope) the damage corresponding to each flight condition. A similar process is inevitable in the case of the loads, due to accelerated flight, if fatigue damage from this cause is to be considered. Information is thus needed giving the frequency of loads of each order due to control operation, landing, ground handling, and gusts.

No mention has been made so far of how the required data are to be collected ; how accurate are the assumptions ; and what is the allowance to be made for departure from the " most probable " figures used in calculations. To recapitulate: it is necessary in order to assess the suitability of a particular structural element to know :—

(i) the stress (in the form $M \pm R$) corresponding to each flight condition and manoeuvre,

(ii) the probable frequency of each occurrence (i) during the life time specified,

and (iii) the life of the element under various ranges of reversed stress.

Theoretical analysis of the rotor will indicate the critical points of the steady flight envelope, and together with results from strain gauges, will enables the pattern of stress to be comprehended. A conservative assumption such as that already suggested could be employed to reduce consideration of steady flight to a few cases only. The stress cycle (at mean zero stress) equivalent to each load may now be found by the modified Goodman relation. This is again conservative. Great care must be exercised in the selection of S—N data corresponding to reversed stress. The effect of notches, etc.,

makes it very desirable, if not essential, for at least a few control tests to be performed on the actual structural element, under a load distribution similar to that occurring in flight. A margin of safety must be allowed because of the scatter associated with all experimental fatigue results. Alternatively, an S—N curve may be used giving a number of reversals to failure that is rarely *not* exceeded (not more than 1 in 10^4 times, say). That it is very difficult to draw such a curve may be appreciated from the results of one series of laboratory tests which, although exceptionally carefully controlled, show a variation of life between 0.25 and 40 million cycles in 216 tests at the same load. The margin may be provided by applying a factor of safety to either the load or the life. The number of reversals in the case now being considered is large, and hence a factor on life is not convenient. From the figures just quoted, such a factor might have to be greater than 100, but would vary with the expected life of the aircraft. In some designs the rotor will have an indefinite life under steady flight conditions alone : in this case a factor on life becomes meaningless. The author prefers to apply a factor to the load—that is, to both the steady and alternating parts. This factor should cover the error involved in the correlation of different loads by the concept of cumulative damage.

A similar process must be followed in calculating the effect of acceleration loads, though in this case the basic information relating to the stresses and frequency of application is not available. The stresses due to control operation and gusts may be calculated, although at some length and without much accuracy. Data also exist from which the frequency of gust loads may be deduced, but these loads are not usually so severe as control-induced loads, the frequency of which is quite unknown.

There is a very real need for information on acceleration stresses in blades ; this could be provided by strain gauges in conjunction with a recording device similar to the V-g recorder in use on aeroplanes. Such an instrument would enable allowance to be made for all transient stresses, whether due to taxying, starting, manoeuvring, or any other accelerated regime.

At present, then, owing to the lack of essential knowledge, it is not possible to ensure absolutely that fatigue failure will not occur during the specified life. It is suggested that a fatigue factor of 1.5 be applied to the steady flight loads, it being a requirement that the structure shall not fail in fatigue during the specified life of the aircraft under these fully factored loads alone. In addition there should be an ultimate factor of 2.0 on the maximum loads occurring from any cause. It is hoped that this will ensure that peak loads do not damage the structure to such an extent that it fails subsequently under the steady flight loads.

In the future, when enough information has been collected, it will be possible to apply the cumulative damage theory to all the loads. A factor must then be applied to life, because deviation in practice from the " most probable " frequency is essentially a change in the number of occurrences. A factor of, say, 4 should be applied to the frequency of each stress, as derived from flight acceleration records. The fatigue load factor should then be reduced, since the fatigue effects of all loads will have been included. The factor will still have to account for error in calculated loads, for sub-standard strength due to material faults, corrosion and other service damage, for faulty workmanship and the spread of experimental results in constructing the S—N curve. The author is of the opinion that this factor will be about 1.25.

The Navigation of the Helicopter

By R. W. USHER, B.Sc., F.R.Met.S.

A Lecture presented to the Helicopter Association of Gt. Britain, 25th September, 1948, in the library of The Royal Aeronautical Society, London, W.1.

H. A. MARSH, A.F.C., A.F.R.Ae.S., IN THE CHAIR

INTRODUCTION BY THE CHAIRMAN.

LADIES AND GENTLEMEN,—As you know, this is the first lecture of our 1948/49 Session—a series which I am sure you will find both interesting and instructive. It is also the first time we have been privileged to use this room for our Meetings and our thanks are due to the President and Council of the Royal Aeronautical Society for granting us this facility.

Our lecturer today has chosen a subject which is becoming of very great importance now that Helicopters are being used in a definite operational sense. Mr. USHER is peculiarly well suited to talk to us on "Navigational Aids to the Helicopter" as he is qualified as a R.A.F. Advanced Specialist Navigator, and has some experience of Helicopter Pilotage. He is a Fellow of the Royal Meteorological Society and an Associate of the R.Ae. Society and, needless to say, a Member of our Association and also holds the Bachelor of Science Degree and Diploma of Education—both of London. His present appointment is with the Ministry of Civil Aviation as a Member of the Examining Staff for Personnel Licences, and as such will obviously have a very close contact with Navigational problems.

A cordial welcome is extended to our visitors, also to those new members who have not previously attended our meetings.

MR. R. W. USHER.

Introduction.

The helicopter is designed to provide air facilities which fixed wing aircraft cannot supply, *i.e.*, short range trips with the minimum amount of inconvenience to passengers, and the maximum speed of transit. It has been variously estimated that the helicopter is more efficient from the point of view of the time factor than other forms of transport over distances between 250 and 400 statute miles. Making an allowance for the optimism of the enthusiast and for adverse weather conditions, which affect

The author wishes to thank the Director of Meteorological Services for the courtesy to utilise the above figures, and for the valuable criticism of this paper made by members of his staff, a resume of which is available in the full paper.

helicopter operations more seriously than fixed wing aircraft, it may be assumed that the estimated distance for the efficient transit of passengers and/or freight is 200 statute miles.

For the United Kingdom helicopter operations will first assist fixed wing operations, and eventually supersede them completely within a relatively short period, when the larger type helicopter is available. The purpose of any paper on Navigation will thus be to review the present method of internal transport, and then put forward the basic requirements for the helicopter to do, at first, precisely the same work, and eventually to increase this work, as the fixed wing aircraft. What is more, the criterion must be that the use of helicopters for internal transport will be more efficient than fixed wing aircraft.

From the figures issued by the British Division of the British European Airways the initial target becomes :—

Passenger load factor : 63·4%	Annual utilisation : 1.156 hours
Revenue load factor : 53·4%	Percentage regularity of service : 95·2%
Average passenger load : 6·9 persons	Average length of stage : 102 st. miles.
Average freight load : 1,289 lbs.	

Average length of hauls : 137 st. miles passenger ; 150 st. miles freight ; 130 st. miles mail.

Note : The figures quoted are for the period April, 1947, to February, 1948.

Stage Distance. It has been shown that up to 200 miles, or even further, the helicopter is more efficient than the aeroplane. Thus nearly every one of the stages completed by B.E.A. British Division fall within this category.

Load. Helicopters are in the prototype stage which will carry either :

(i). 3 passengers or 750 lbs.
(ii). 12 passengers or 4,200 lbs.
(iii). 24 passengers of 8,500 lbs.

These latter two types will be able to handle the average loads as stated in the above figures.

Annual Utilisation is an engineering problem, and outside the scope of this lecture. It seems possible that the helicopter will become as mechanically efficient as the present aeroplane.

Regularity of Service. The average figure of 95% is the initial target, and it is with this figure in view that the main thesis of this paper is concerned. To arrive at a reasonable statement of the problem the paper is set out in the following form :—

Part II. The need for a navigation aid.
* Part III. The navigation aids that are available.
* Part IV. The requirements for helicopter navigation and the aids that meet these requirements, at least in part.

Before discussing the subject of Navigation is it advisable to examine the present position in the U.K. and at the same time remember that the provision of navigation aids for the helicopter, if required, should not greatly increase the present telecommunications system. Also, it is submitted, that

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Parts III and IV were not delivered as part of the Lecture, but are available in the Association Library for reference.

helicopter operators should bear in mind when ordering navigation equipment, or asking for its provision by the State, the initial cost of installation, operation, and maintenance, and compare this with the increased services that such systems would provide. It may well be that the cost of installing such navigation aids will far outweigh the benefits that will accrue from their utilisation.

The present situation. Most of the flying taking place in and over the U.K. does so during daylight hours. In fact is it questionable that night services in this country bear any advantage over rail transport when the important question of passenger comfort is discussed.

It would appear that there is little call for night services for passenger traffic at least in the U.K. internal services. Thus it may be established that the majority of the civil flying in the U.K. will take place during the daylight hours.

To accommodate this traffic, which is a substantial proportion of the total air traffic into the U.K., a vast organisation has been created.

> *Aerodromes.* There are 132 aerodromes in the U.K. available to civil aircraft. Of these 62 are civil aerodromes, 50 are R.A.F. aerodromes, and 20 private aerodromes. Of this total 71 have no facilities for night flying and 5 have limited facilities. Of the civil aerodromes, 34 have no facilities, 5 have limited facilities, and to this list must be added 18 private civil aerodromes which also have no facilities. This substantiates the assertion that much of the air traffic in the U.K. is solely in the daylight hours.
>
> *Telecommunications.* To assist this air traffic and provide information for control purposes a comprehensive network of radio stations and installations is available. Details of this may be found in "Notice to Airmen," No. 16048 and Amendments.

Note : Not all these systems and aids are used exclusively for internal net-works. It is difficult to separate the utilisation of the telecommunications net-work of the internal and international routes. But if it can be shown that the helicopter can replace the aeroplane on all internal routes, then the country will require about eight major airports to handle the international traffic, and a number of small landing areas to handle the inter-connecting helicopter services. These landing areas can be situated close to, or inside, the towns, thus increasing the over-all speed of passenger and/or goods transit. There are further considerations :—

(*a*) There would probably be a reduction in the telecommunications net-work.
(*b*) There would certainly be a reduction in the number of airfields available for civil aircraft, and, as a consequence,
(*c*) The land could be returned to use for the production of food.

The Problem of Navigating the Helicopter.

THE NEED FOR A NAVIGATION AID.

Purpose.

The purpose of this paper is to attempt to study the need for a navigation aid for helicopter operations, and the advisability of introducing ground aids. To date, it has been assumed that the helicopter must be equipped with a blind flying panel and a reliable navigation aid before it can operate commercially with safety and regularity. This paper attempts to show that, except for certain limited areas at definite periods of the day, the helicopter can operate during *daylight* hours with up to 98 per cent. regularity of service without any additional equipment.

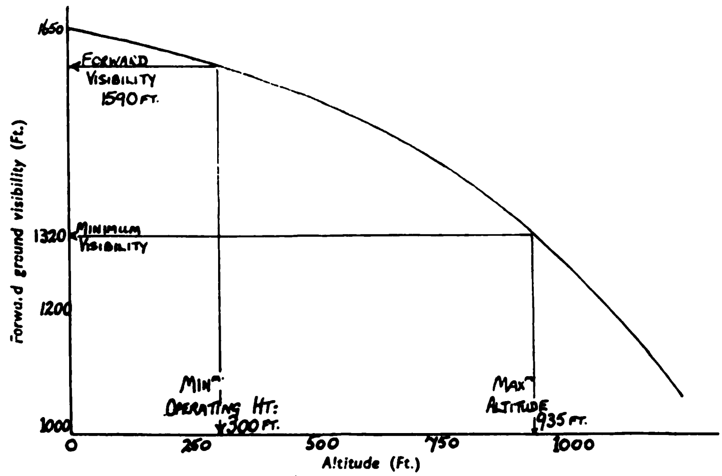
Factors preventing regularity of service.

The phenomena which may interrupt any air operations of aircraft are :—

Weather.

Reduced visibility. It has been reliably stated that the helicopter can operate in reduced visibility conditions of 440 yards with safety, and still maintain a schedule. Thus at an altitude of 1,000 feet above the surface, to obtain a forward ground visibility of 440 yards, the slant visibility will

DIAGRAM 1. The visibility condition is 550 yards



have to be 550 yards. Diagram 1 shows the relationship between forward ground visibility and slant visibility. The figure of 1,000 feet altitude is taken because it seems unlikely that the helicopter will operate at much greater heights than this. The number of occasions when the visibility is less than 550 yards is determined in the following paragraphs.

The consideration of visibility must also include a mention of night flying. The basic need for night flights must be

(*a*) increased stability of the machine ;
(*b*) a blind flying panel ;
(*c*) a navigation aid.

These problems still await a solution, and although the Americans have granted Certificates of Airworthiness to the S.51 and the Bell 47 for operation at night the number of occasions when this will be possible will small, and at any rate too unreliable to assess for use with scheduled operations. But because these problems have not been solved, there is no need to halt the commercial development of the helicopter for daylight operations.

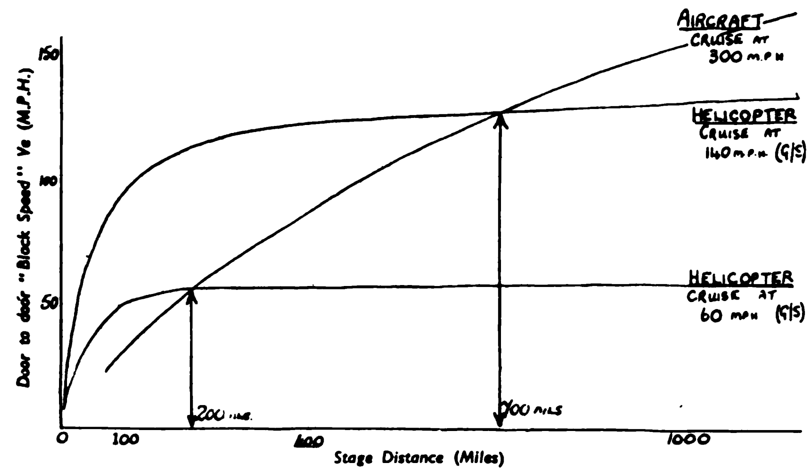
High winds. It is inadvisable to operate the helicopter in high winds for two reasons :—

(*a*) Starting and stopping the main rotor blades is complicated by the buffetting they will receive, which is likely to damage the blades.

(*b*) From the point of view of this paper, the effect of the wind on the ground speed of the helicopter is more important. If the limit of operation of the helicopter is in winds of 40 m.p.h., then with present-day machines, assuming an air speed of 80 m.p.h., the ground speed will vary between 40 and 120 m.p.h., depending on the assistance the machine is receiving from the wind of otherwise. This will increase the cost of a single operation over a particular route, and will have to be allowed for in the final analysis of costing helicopter operations. It would, for instance, have a considerable effect on the figures given for the comparative speeds of different transport systems (Raoul Hafner Lecture and article in " American Helicopter "). This is shown in Diagram 2, when the figures postulated by Hafner are subjected to a head wind of 40 m.p.h. For interest, the same analysis is given for a tail wind component of 40 m.p.h. in Diagram 2.

Although this wind effect should be noted, the number of occasions when the wind exceeds this maximum figure is less than 1% of the total observations. For the purposes of this analysis this item can be ignored.

Diagram 2



Low cloud base. When the cloud is too low to offer a prospect of flight under contact conditions with safety then once more operations will have to be suspended. This low height limit is taken to be 500 feet above the surface of the earth. The number of occasions when this occurs as an isolated phenomena is small. Usually, low cloud covering the high ground in the vicinity is associated either with high wind and/or rain. Thus these occasions will be included in the reports for lowered visibility, and there is no need to make a special study here of this effect.

From Diagram 2 it would appear safe to say that for distances up to 200 statute miles the helicopter is more speedy than any other form of transport. This figure is also supported by Chawla, an American economist,

who postulates a maximum figure of 250 statute miles, and our President, Mr. Marsh, who also has estimated this distance as 200 statute miles.

Rain. Rain generally lowers the visibility to approximately half that prevailing in clear conditions at the time. Thus the occasions when this phenomena is likely to interfere with helicopter operations by lowering the visibility will also be included in the visibility figures. It is assumed that the helicopter will be able to operate in light rain which does not reduce the visibility to less than 550 yards, although at the present time it is feared that the main rotor blades will suffer damage by pitting. The introduction of blades made by substances other than fabric will overcome this problem.

Snow. No known information is available on the behaviour of the helicopter under icing and snow conditions. In any case snow reduces the visibility below 550 yards and is thus included in the visibility figures. Icing is not assumed to present a difficult problem as the helicopter pilot will not enter ice-forming cloud. The problem will be overcome for the present by default rather than solution.

Comment. These weather phenomena can all be included when a study of the reports of visibility is made. The number of occasions when one of the above phenomena occur and *at the same time* the visibility is greater than 550 yards is assumed to be negligible.

Mechanical Unserviceability.

This effect will also reduce the regularity of helicopter operations but is overcome by the introduction of reserve machines. This problem does not fall into the compass of this paper, but is one that should be discussed when the ecomonics of operating the machines is studied.

Provisional Target.

The helicopter is to augment and finally supersede the air transport services at present available in this country. Thus the first target is to equal the figures issued by the B.E.A. British Division for passengers carried, freight carried, utilisation, and regularity of service. The relevant details are :—

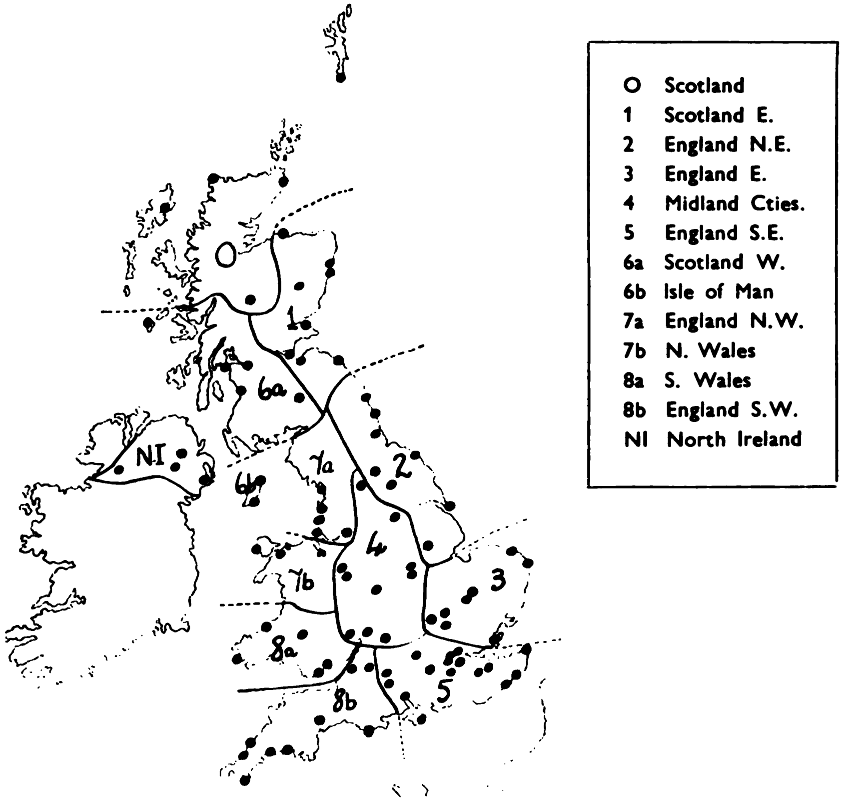
Passengers carried per aircraft-trip : 7.
Freight carried per aircraft-trip : 1,289 lbs.
Average length of haul : 133 statute miles.
Annual utilisation : 1,156 hours.
Percentage regularity : 95%.

As it is anticipated that the helicopter will operate over short distances, less than 200 statute miles per stage, and the new machines, at present in the prototype stage, will be designed to cope with the above passenger and less than 200 statute miles per stage, and the new machines, at present in freight loads, the two factors left for comparison are the annual utilisation, and the percentage regularity of service. The former will be studied in any analysis of the economics of operation of the helicopter. The latter is the basis of study of this paper, and the figure of 95% regularity of service is taken as the minimum requirement for this initial stage.

Method.

The British Isles was divided arbitrarily into thirteen areas corresponding with the division of the Meteorological Office (see Diagram 3). A number of Reporting Stations were selected for each area and the endeavour made that the area was adequately covered for synoptic information. This was accepted on the premise that the helicopter will operate, in the main, either local services of a radius of 80 statute miles from the base to augment and

DIAGRAM 3. REPORTING STATIONS AND AREAS



feed other air services, or direct stage distances of not more than 200 statute miles. This latter would cover two of the areas and both would have to be studied to obtain a reasonably accurate estimate of the regularity of service that may be expected on such a route. Despite this arbitrary choice of areas and Stations it is felt that any change in this division of the country would not materially affect the final conclusion.

The synoptic reports from these Stations for each of the areas was studied for the period 1942-46 inclusive. A five-year period was considered the minimum to obtain reliable results. The visibility reports only were studied, as explained on page 32, and in order to standardise these readings,

the reports given at six-hourly intervals were considered to be issued in the middle of such an interval, *e.g.*,

Report at 03.00 hours valid for 00.00-06.00.
Report at 09.00 hours valid for 06.00-12.00.•
Report at 15.00 hours valid for 12.00-18.00.
Report at 21.00 hours valid for 18.00-24.00.

Also for the years 1942-44 reports were issued at 07.00 and 13.00 hours. These were considered to be virtually the same as the 09.00 and 15.00 hour reports, and were included with them. In order to conform with para. 1, page 27, the reports were split into day and night, day being considered to last from 06.00-18.00 hours. This would have the effect of making the results of the analysis conservative, as the figures would include part of the winter night hours when flying would be restricted by conditions other than the visibility, and they would exclude the periods in the summer months when good flying weather is experienced up to 22.00 hours.

From the reports sub-divided in this manner, the visibility conditions were compiled for each of the meteorological code figures, and the results tabulated. From these figures the percentage of the occasions when the reports gave a visibility Code 2 or less (550 yards or less) were taken for each of the areas.

Note : The Tables on which the final Table I was constructed are included in the full paper in the Association Library.

These percentages were then summarised for the five-year period : see Table I.

In the preliminary Tables used to construct Table I the figures are given for the night observations although no detailed analysis is made of these figures. Both the S.51 and Bell 47 have been given Certificates of Airworthiness to operate under contact conditions at night, *i.e.*, provided that a natural horizon is available. In order to obtain an approximate figure of the expected regularity of service of such an operation the minimum condition for the visibility is taken as 2.25 statute miles, *i.e.*, Code figure 6. This approximate figure will not consider the effect of moonlight on such operations.

Results.

Day. From Table I it will be seen that over the five-year period the number of occasions when a helicopter, as at present equipped, cannot operate varies with the area, and in no case exceeds 5%. Thus at the present time the helicopter can give a 95% regularity of service.

This means that any navigation aid will have to increase the regularity of service from 1-4%, assuming that the best figure to be obtained for regularity of scheduled operations if 99%, which is high when compared with other forms of air transport.

Because of the very small increase in regularity that must be attained, the navigation aid may not be of a universal nature, such as GEE, because the aircraft utilisation of this aid will be so small as to make the actual cost of operation in terms of improvement of service quite high.

Thus the aid required will have to be of a local nature, providing homing facilities with light equipment in the aircraft. This is to allow the aircraft to have maximum payload, and not have to carry a navigation aid* which will occupy space and weight, when the number of occasions on which it

**Note*: It is proposed to discuss the navigation aid required on another occasion

is to be used will be small, and thus increase the actual cost of operating the equipment per occasion used.

The regularity of service compares favourably with the figure achieved by B.E.A. British Division. Also it should be noted that the helicopter will be able to achieve a better door-to-door time for each of the stages of the flights. This factor of 95% can be improved in the near future.

The B.E.A. helicopter operations should, according to these tables, have achieved a regularity of serv ce of 98% in the Yeovil area. The figure obtained was 96% regularity of service during the worst flying months of the year. For the Norfolk area, with operations taking place in the better flying weather, June-August, the figure should be better than 97.7%.

The helicopter, as it is equipped at present, can achieve a better figure for reliability of service than the fixed wing aircraft without the aid of a blind flying panel or a navigation homing aid. This is true of *day flying only*, but the majority of British internal services operate during the day.

TABLE I.

Observations. Summary, Years 1942-46.

The following Table is a Summary of the results for the period concerned. The percentage of the occasions when the visibility is below the prescribed minimum of 550 yards is tabulated against the areas concerned, and an average taken over the five-year period.

Area	1942	1943	1944	1945	1946	Minimum Average
Scotland, N.	1·2	1·2	2·0	1·0	1·9	1·5
Scotland, E.	1·1	1·2	1·3	1·4	1·5	1·3
Scotland, W.	1·6	1·5	1·0	1·8	1·3	1·4
Isle of Man		0·2	0·9	1·7	0·6	0·9
England, N.E.	2·4	4·1	2·9	2·4	2·8	2·8
England, E.	1·8	2·6	3·2	2·0	1·8	2·3
Midland Cities	4·6	4·9	4·5	4·9	3·0	4·4
England, S.E.	2·7	3·1	2·5	3·4	1·8	2·7
England, N.W.	3·6	3·6	3·0	4·5	2·4	3·4
N. Wales	1·2	1·8	0·9	1·0	0·3	1·0
S. Wales	2·4	1·2	1·8	3·1	1·3	2·0
England, S.W.	1·7	1·5	1·6	3·8	1·4	2·0
N. Ireland		1·2	1·1	2·2	1·2	1·2

Anomalies in the Observations.

There are a number of places which have reported throughout the year minimum visibility conditions of less than 550 yards for more than 5% of the total reports. These places are listed in Table II. At first glance this looks a formidable list covering large sections of the British Isles. But in all cases except three the reports show that the reduced visibility is due to morning local fog which clears rapidly by mid-day. All these mid-day figures show a reduction to less than 5% of the observations which falls below the prescribed limiting figure. The places which report persistent minimum visibility of 550 yards on more than 5% of the observations are coastal areas away from populated areas, and the conditions are produced by persistent sea-fog.

Note : The full Table II is available for inspection in the full paper in the Association Library.

TABLE IA.

The following table is a summary of the results of the same period when the visibility conditions are less than 1,000 yards Code 3. The figure for the expected percentage of occasions when the helicopter will be unable to operate owing to reduced visibility is nearer to the average in Table I than in Table IA. An estimate is made of the expected figures by weighting the results obtained. This is given in Table IA.

AREA	1942	1943	1944	1945	1946	Maximum Average	Estimated Percentage
Scotland, N.	2·6	1·4	2·4	1·5	2·5	2·1	1·6
Scotland, E.	3·3	2·6	2·0	2·8	2·2	2·6	1·6
Scotland, W.	3·6	3·0	3·0	3·6	2·6	3·2	1·8
Isle of Man		1·2	2·0	3·4	0·9	1·5	1·0
England, N.E.	5·0	6·5	5·2	4·8	5·2	5·3	3·3
England, E.	3·6	5·0	4·8	4·0	3·4	4·2	2·7
Midland Cities	9·0	9·0	8·5	9·2	5·5	8·2	5·2
England, S.E.	5·4	5·0	4·0	6·0	3·6	5·4	3·3
England N.W.	7·2	7·2	7·0	8·0	7·0	7·3	4·2
N. Wales	2·6	4·0	1·2	2·4	0·9	2·2	1·2
S. Wales	3·6	2·0	3·4	3·8	2·4	3·0	2·3
England, S.W.	2·6	3·0	3·0	4·8	1·8	2·3	2·3
N. Ireland		2·0	1·9	2·6	1·8	2·1	1·4

The table was weighted by allowing a balance of four times the average in Table I to one of the average of Table IA. This purely arbitrary method of estimation is designed to bring the results near to the proscribed visibility minimum of 550 yards.

This table also allows for a 20% error in the observations made under Code 3, *i.e.*, on 20% of the occasions that Code 3 was reported it was in fact so near the limiting *figure* of 550 yards as to preclude helicopter operations.

To assist helicopter operations into these areas, the correct scheduling of aircraft would achieve the desired end. It may be that some form of ground aid would also be desirable.

Congested Areas.

It is thought improbable that single-engine helicopters will be allowed to operate into towns unless the track follows a route which provides suitable landing areas in case of emergency. These landing areas should be of the order of 300 by 150 feet, and spaced approximately half a mile apart. Inspection of a number of towns will prove that few can offer this facility. The figure of half-a-mile is derived :—

> The normal operating height will be 1,000 feet above the highest point on or near the track.
>
> The normal descent in autorotation will be at 1,200 feet per minute at 45 m.p.h. indicated forward speed.
>
> Thus the time of descent will be 50 seconds plus time for " flare-out " and landing, during which time the helicopter will have travelled five-eights mile. Allowing a factor for wind, turning into wind, etc., the optimum figure becomes half a mile. If the disc loading on helicopters is decreased, which is away from present development trends, then the glide may be made more shallow and the distance between landing areas increased.
>
> Thus the operation of single-engine helicopters into congested areas will be precluded.

TABLE II. ANOMALIES OF THE OBSERVATIONS.

A number of individual stations report less than 550 yards visibility on more than 5% of occasions. These are listed below to show, except in three cases, this is only true of the morning or the evening reports, but that the phenomena causing the low visibility clears before mid-day and in the afternoon, allowing operations under the conditions that have been proposed.

These stations are listed below, and the Table gives the morning, mid-day, and evening reports to show the clearance. This is an important point, if it is proposed to schedule helicopter services into these areas.

Place	1942			1943			1944			1945			1946		
Time of Obsvtn.	9	15	21	9	15	21	9	15	21	9	15	21	9	15	21
Bidston Obsy.										5	—	—			
Birmingham	10	1	2·5	6	3·5	4·5	7	2·5	3·5	7	—	—			
Boscombe Down				6	0	5	7	2	2	7	1	3			
Cape Wrath				6	6	6	8·5	5·5	5				5	4	2·5
Catterick	9	2·5	4·5	12	4	5									
Cranwell				9	2	2·5	6	2	2·5	5	1	4			
Croydon				8	3	7·5				5	2	2·5			
Driffield				5	2	2·5	5	1	1·5						
Dunstable	6·5	1·5	2·5	6·5	1	2	9	1	2						
Durham										7	8	3	6	1	4
Eskdalemuir										5·5	1	4			

Place	1942			1943			1944			1945			1946		
Time of Obsvtn.	9	15	21	9	15	21	9	15	21	9	15	21	9	15	21
Felixstowe							5	1·5	1						
Finningley							11	1·5	2·5	7·5	1·5	1	4·5	1	2
Greenwich	5	—	—	10	—	—	6	—	—	6	—	—	4·5	—	—
Harrogate				10	—	—	7	—	—	6	—	—	8·5	—	—
Kew	6	2·5	2·5	10·5	2	3	6	3·5	3·5	7·5	2	4·5			
Little Rissing							10	3	5	10·5	3	6			
Larkhill										7	1	0			
Linton-on-Ouse				9	1·5	1·5	8	2	3						
Littlehampton										7·5	—	3			
Lizard										8	7	7			
Lympne	5·5	1·5	2				9	2·5	3	7·5	2	5·5			
Manston				5	1	2									
Mildenhall				8	1	2·5	6·5	2	2						
Nottingham	13·5	—	—	13·5	—	—	13	—	—	11·5	—	—	8	—	—
Oxford	6	—	—	7·5	—	—	5	—	—						
Ross-on-Wye	6·5	1	1·5							6·5	1	3·5			
Renfrew	5	2	2·5							6	3	3	5·5	—	—
Ringway										6	2·5	2·5			
Rhayder										6	—	—			
S. Farnborough	6·5	0·5	3	9	1	1·5	6	2	5	5·5	1·5	4·5			
Scarborough				7	—	—	6·5	—	—						
Scorton							5·5	2	2·5						
Sealand	5	1·5	1·5												
Southampton	5	—	—												
Southport	5	5	1·5							6	3	—			
St. Ann's Head							6	4·5	5	6	5·5	6			
Tern Hill				5·5	1·5	2	8	1	1·5	7	1	5			
Thornaby				5	2	2·5									
Upper Heyford				8	3	2									
Wisley				7	—	—				6	—	—			
Honiley				10	2·5	3	7·5	1·5	2·5	7·5	2	4·5			

§ Where the spaces are vacant in the table, then the observations for that year do not exceed 5% for the number of times that the visibility is less than 550 yards.

— indicates that the reporting station does not give returns for the times indicated.

§§ for the years, 1942, 1943 and 1944, the reporting times were actually 01.00, 07.00, 13.00 and 18.00 hours instead of the 03.00, 09.00, 15.00 and 21.00 hours respectively. They have been grouped with the nearest time.

COMMENT.

From these figures it has been shown that the helicopter can operate with safety and a higher degree of regularity than the fixed wing aircraft over the British Isles. The need for a navigation aid exists, and although it is an imperative requirement, it is subsidiary to the solution of the problems of greater stability of the machine, and the provision of a blind flying panel. Apart from reasons of economy, if a navigation aid is required to facilitate expanded helicopter operations by day, it will require to be cheap, simple, light-weight, and easy to maintain both for air and ground installations. To illustrate this point : From any of the sets of figures in the tables used to construct Table I, assuming that the safe minimum visibility for fixed wing aircraft is 2.5 miles for contact flight, then there are approximately between 12.7% and 39.6% of the occasions when some aid is required. As this figure is large, it is economically sound to spend a large sum of money on some form of instrument and navigation aids. This is not true of helicopters, and the above observations are made.

The form of the navigation aid which *may* be required for day operations is to be discussed in Part IV of this paper, but outlined it will probably be :

> A ground aid into congested areas, when allowed to operate, marking a safe track by lights every 400 yards or so, preferably leading from a homing beacon outside the congested area. The helicopter will home to a beacon and then proceed in on a specified track, guided by ground installations. *Or*
>
> VHF D/F Homer : A small light installation for homing on to a low power beacon with restricted range. The same frequency can also be used for voice transmission.
>
> A radar homing aid. This has the disadvantage of no speech transmission, but provides the helicopter with range and bearing from a fixed ground installation.

CONCLUSIONS.

1. The commercial development of the helicopter can be undertaken with as high a degree of reliability of service as at present given by the fixed wing aircraft, without the installation of any further instruments or aids.

2. Ground aids can be introduced, in the first instance, at specified points only to assist operations into areas where the reduced visibility conditions tend to lower the regularity of service.

3. During the interim period the problems of stability and of blind flying can be tackled and overcome.

4. Useful data on the operation and economic servicing of the helicopter can be obtained in this period.

5. Given para 3, the helicopter can be provided with navigation aids which will give it, for this country, a regularity of service and speed of operation which the present form of air transport cannot hope to achieve, even with the introduction of " all weather flying."

Mr. A. McClements Vote of Thanks to Mr. Usher.

It gives me great pleasure to thank Mr. Usher, on behalf of the Association, for presenting to us today part of his paper on " Navigational Aids for the Helicopter."

That Mr. Usher has chosen for his paper a subject of the utmost importance is obvious, and it is gratifying to us all to know that a man of his calibre is giving intensive thought to the overall problem. We look forward with interest to reading the remainder of his paper which, I am sure, will be a contribution of the utmost value.

From the discussion we have just heard, it is apparent that we have a long way to go before we reach a solution to our navigational problems acceptable to us all. Nevertheless, so pressing is the need for an early solution, that we must proceed vigorously in our researches. It is my impression that the technician must provide, before long, an aid which is both simple in presentation and accurate. If he does not, commercial exploitation of the helicopter will be seriously handicapped because full utilisation by flying under bad weather conditions during day and night will not be possible as soon as we wish.

I think it only remains for me to thank Mr. Usher again and to request you to signify your appreciation in the normal manner.

* * *

Discussion.

The Discussion following Mr. Usher's Lecture will be reproduced in the next issue of the Journal.

Obituary

J. A. McMULLEN, M.B.E.

Pioneer of Rotary Wing Flying.

August 15th marked a very sad day for members of the Association and all other rotary wing enthusiasts, in that our oldest amd most respected Founder Member passed away as the result of a serious operation at the age of 84.

Mr. McMullen, or " Mac " as he was affectionately known, will be remembered by all rotary wing devotees as the first pupil of the Autogiro Flying School and the first private owner of an autogiro in this country. In fact, it was as the result of his purchasing a C.19 Mk. IV autogiro, that the School was formed and " Mac " and I taught each other to fly the aircraft.

During the 1914-18 war he was a Navigation Instructor in the R.A.F. and was made an M.B.E. for his services. He did not take up flying on his own account until 1932 and qualified for the first *ab initio* Autogiro "A" Licence in July, 1932, at the age of 69. His affection for the autogiro was unbounded and he made use of his aircraft to visit friends and relatives in all parts of this country and also Ireland. Some of his navigation ideas were unorthodox and he published a little book on this subject in the early 30's. I well remember the preparations for his trip to Dublin, which amounted to serious study of maps, drawing a few diagrams on plain postcards, then discarding the maps and setting off, but the fact remains that the trip was 100% successful including a forced landing in Cumberland due to fog. A " mock trial " was held on him for this episode which ended by the presentation of a silver tankard from his friends to mark the occasion. His C.19 flying was marred by one serious accident when landing at Hanworth one Sunday with a passenger on board. Looking out to one side he omitted to notice a high tree which caught the opposite side stub wing and the aircraft fell into a pond. Both " Mac " and his passenger had to be fished out, luckily with only a few bruises and a shaking up.

He continued to use a C.19 until about 1937, when the type became extinct, and then bought a BAC Drone and carried on his aerial trips in much the same way. Needless to say, 1939 put a stop to his flying but he took it up again in 1946. The medicos would not pass him for an "A" Licence, but even so he flew around the country visiting with a safety pilot whose sole job was to satisfy the regulations, as " Mac " was perfectly competent to handle the aircraft.

Everyone who had the privilege of knowing " Mac " and being counted amongst his friends will wholeheartedly agree with me that he was one of nature's real gentlemen in every respect. On behalf of the Association I

tried to arrange for a suitable floral tribute, but this was not possible. In response to my wire to General McMullen, Mr. McMullen's only son, I received the following reply :—

> "Your telegram deeply appreciated. Cremation took place Tuesday and ashes were taken by air from Broxbourne Aerodrome and scattered at sea. There were no flowers by request but very many thanks for kind thought. McMULLEN."

I should like to end by saying "And so passes a Grand Person."

H. A. MARSH.

18*th August*, 1948.

*   *   *   *   *

It is with regret that we also have to announce the death of two other members of our Association :

Mr. P. W. Howes—in an aircraft accident on July 2nd, 1948,
and
Lt. (A.) E. J. Ockelford, R.N.—in an aircraft accident, July, 1948.

IMPORTANT NOTICE.

CHANGE OF ADDRESS.

Thanks to the generous response of the Aircraft Industry to an appeal for funds made on behalf of members by our Chairman, the Association has now been able to acquire its own office accommodation.

The appeal of our Chairman was made for the specific purpose of obtaining enough funds to establish our own offices, made necessary by the increase in the Association's activities. Great inconvenience was found in sharing the original office accommodation at Finsbury Circus House.

The Association would like to place on record its appreciation for the generosity displayed by the following firms :

The Bristol Aeroplane Co.	Firth Helicopter Ltd.
The Cierva Autogyro Co.	Irvin-Bell Helicopter Sales Ltd.
The Fairey Aviation Co.	Pest Control Ltd.
The Westland Aircraft Co.	

The request was a specific one for £50 per annum for three years from the larger firms and £25 per annum from the smaller ones. The majority of those approached have guaranteed the sum requested, the others will review the situation annually. Mr. J. G. Weir, on behalf of the Cierva Autogiro Company, sent a cheque for £250 to cover the request and the remainder as a contribution to the Reserve Fund.

Members should note that as from August 1st, 1948, the Association's Offices have been moved into Londonderry House, 19 Park Lane, London, W.1, the new telephone number being GROsvenor 1771.

Members are reminded that they are welcome to call at the offices at any time, and it is hoped that soon there will be a small library of helicopter literature besides the usual selection of aeronautical magazines, etc.

It whould be noted that the registered address of the Association remains at Finsbury Circus House, but that all future correspondence should be addressed to the new premises at Park Lane.

THE JOURNAL OF
THE HELICOPTER ASSOCIATION
OF GREAT BRITAIN

VOL. 2. No. 3.

1948

The Journal of

THE HELICOPTER ASSOCIATION OF GREAT BRITAIN

ISSUED QUARTERLY | Oct.—Nov.—Dec., 1948 | PRICE: 10/6

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CONTENTS

ANNOUNCEMENTS

OBJECTS OF THE ASSOCIATION

The objects of the Association are to collect, compile, and disseminate information of a technical and semi-technical nature pertaining to Helicopters, and all other types of Rotating Wing Aircraft.

The Association aims to work in close co-operation with existing Aeronautical Bodies on matters affecting its Objects, and it may act as an Advisory Body in the promotion of legislation calculated to be of benefit to the development of Rotating Wing Aircraft.

THE PRESIDENT
(1949 – 1950)

JAMES G. WEIR, ESQ., C.M.G., C.B.E., F.R.Ae.S.

Prior to any practical achievement in engineering science there is always a group of pioneers who pave the way towards the solution of the problems. Foremost of such a group in the rotary wing field, Mr. J. G. WEIR, was the first person in this country to realise the possibilities of rotary wing flight and was instrumental in establishing the late JUAN DE LA CIERVA in Great Britain in 1925. In 1926 The Cierva Autogiro Company was formed, of which he has been Chairman since its inception. It was due largely to his faith in those early experiments that the successful evolution of the Helicopter has come to pass.

The Journal of

THE HELICOPTER ASSOCIATION OF GREAT BRITAIN

Editorial Offices: Londonderry House, 19 Park Lane, London, W.1. Tel.: Grosvenor 1771

Vol. 2. No. 3. Oct.—Nov.—Dec., 1948. PRICE: 10/6.

Editorial

Three events of importance in the history of the Association mark the passage of the last three months.

Firstly, the decision by the Council that the time had arrived to bring into use the office of President of the Association, and the election to that office of the first President—J. G. WEIR, ESQ., C.M.G., C.B.E., F.R.AE.S. The Association is honoured by Mr. J. G. WEIR'S acceptance of this office, and his enthusiasm for the Rotating Wing Aircraft will do much to further the objects for which it was formed.

Secondly, the Joint Meeting with The Royal Aeronautical Society proved to be an event of outstanding interest to members. In all, some 400/500 members of the two organisations attended the meeting, of which our membership was very well represented. The five papers read to the meeting covered much useful ground, and the discussion which followed was most illuminating. Through the courtesy of The Royal Aeronautical Society this material is being made available to the Publications Committee and the whole of the Joint Day Discussion Proceedings will be reproduced in the next issue of the Journal.

Lastly, but by no means the least, comes a matter of finance. The Associations' financial position has never been a particularly strong one, and in order to meet this and to provide for increasing expenditure with increasing activities in the future, the Council have decided to make available some space in the Journal for full and half page advertisements. This meets several specific requests which have been received over a period. Since the financial problems associated with the publication of the Journal are very much the concern of the Publications Committee, it is gratifying to see the immediate response to this decision. Although the circulation is, as yet, relatively small, the Journal does have one unique feature in that it finds its way straight to the heart of the whole Rotating Wing movement in this country, as well as in many countries overseas.

That the sound financial status of the Association is also very much the concern of its individual members is witnessed by the unanimous vote at the Extraordinary General Meeting to increase our own subscriptions, of which a full report is contained elsewhere in this issue. With this strengthening the Association continues to make satisfactory progress in its aims, to the benefit of its members and to the advancement of the Science as a whole.

SIXTH LECTURE 1948

Automatic Stabilisation of Helicopters *

By G. J. SISSINGH, DR. ING.

A lecture presented to the Helicopter Association of Gt. Britain, on Saturday, 23rd October, 1948, in the library of The Royal Aeronautical Society, London, W.1.

H. A. MARSH, A.F.C., A.F.R.Ae.S., *in the Chair*

INTRODUCTION BY DR. J. A. J. BENNETT.

Mr. Chairman, Ladies and Gentlemen,

It is a pleasure to introduce our lecturer this afternoon. Although as a fellow-member he has remained modestly in the background until now, DR. SISSINGH is known internationally as a leading aerodynamicist in the rotary-wing field.

Perhaps his first notable contribution was a paper published in " Luftfahrtforschung " exactly 10 years ago ; this was later translated into English and became an N.A.C.A. Technical Memorandum. In his calculations DR. SISSINGH was not content with a rough estimate of the average values of drag coefficient and induced velocity but took into account their distribution along the blade. This unwillingness to make empirical assumptions merely for the sake of mathematical simplicity is typical of his subsequent work.

For a number of years DR. SISSINGH has devoted his attention to helicopter stability and has written extensively on this important problem. His investigations were conducted first at the Flettner Company near Berlin, then at the well-known Kaiser Wilhelm Institut at Göttingen, and recently at the Royal Aircraft Establishment.

There is no one more competent, therefore, to talk on the " Automatic Stabilisation of Helicopters." We have all had a vague idea of the effectiveness of certain devices developed for this purpose in the United States, and this afternoon DR. SISSINGH has undertaken to clarify the position and to tell us exactly what can be expected of automatic stabilisers in the future.

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DR. G. J. SISSINGH.

Mr. Chairman, Ladies and Gentlemen.

Before I proceed to deliver my paper, I would like to acknowledge that I am greatly indebted to the Ministry of Supply, and to Group Captain LIPTROT in particular, for permission to do so, and also for having given me the opportunity and facilities for continuing my work on this subject. I wish also to express my thanks to the Council of the Helicopter Association for the great honour done me by allowing me to address you this afternoon.

My lecture today deals with the automatic stabilisation of the helicopter in hovering flight and is mainly concerned with the Sikorsky configuration. You all know that this configuration is inherently dynamically unstable in the low speed range and that after a disturbance an increasing oscillation builds up. Therefore, an automatic control device is very desirable. It would not only be a help to the pilot but would also be a very great advantage for night and blind flying operations, which at present are only possible under " contact conditions " or with the use of instruments.

During recent years some American firms such as Bell and Hiller have already made an encouraging beginning with automatic control. We know that the results still leave something to be desired, but it is at least a start. We shall try to find out how these control devices work and what is still wrong with them.

I want to avoid going into the mathematical complexities of the problem, in order to make the main points as clear as possible. Any of my listeners who wish to go into the theoretical side more thoroughly are referred to various R.A.E. reports on this subject which are to be published in the near future.

FUNDAMENTALS OF CONTROL DISPLACEMENTS NECESSARY TO GOVERN AN UNSTABLE HELICOPTER.

At first sight the problem of automatic control and stabilisation looks very complex. But it becomes much simpler if we tackle it in a roundabout way by first investigating the effect of given periodic control displacements on the dynamic stability.

The investigations have shown that it is sufficient if we restrict ourselves to control displacements which are proportional to and in phase with

(1) the attitude of the helicopter, and

(2) the angular velocity of the helicopter,

and a combination of these two types. The former corresponds to a kind of static stability and the latter to a kind of damping. The control displacements mentioned above are illustrated in Fig. 1 for a disturbed longitudinal motion (1a being a sketch of the angle in pitch against time). The curves of 1b and 1c show the attitude and the angular velocity of the helicopter and the broken lines give the corresponding control displacements, where a negative control displacement means the lift vector of the rotor is tilted forward.

At present it does not matter how these control displacements are brought about. As an example we can imagine that we have installed an ideal autopilot which carries out the desired displacements without any time lag.

We shall now investigate the effect of our hypothetical autopilot by means of stability charts. These charts are calculated from the frequency

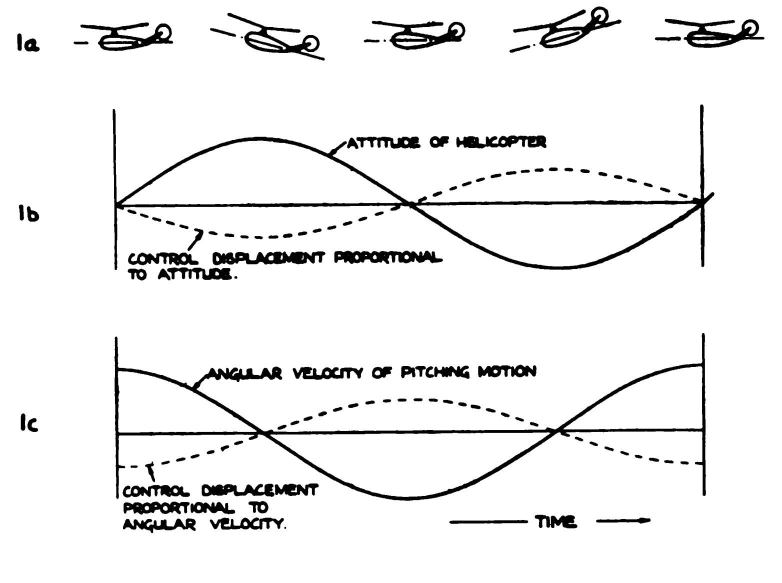


FIG. 1

equation, which (if we consider the flapping motion of the blades as a sequence of steady motions) is of the 3rd order and may be written as

$$\lambda^3 + A_2\lambda^2 + A_1 \lambda + A_0 = 0$$

where for the Sikorsky configuration with the controls fixed $A_1 = 0$. I do not wish to trouble you with the calculation of the coefficients A_0, A_1, A_2, but would like to point out that they depend on the layout of the helicopter and can only be varied within certain limits for a given design. It can be proved that periodic control displacements effect a change of the coefficients. For the Sikorsky configuration it follows that

A_0 is not affected by control displacements,

A_1 is proportional to control displacements in phase with the attitude of the helicopter, and

A_2 increases with control displacements proportional to and in phase with the angular velocity of the helicopter.

Routh's stability criterion requires that A_1 must be greater than A_0/A_2; therefore we cannot achieve dynamic stability in the Sikorsky configuration without control displacements in phase with the attitude.

We will now go into this problem more thoroughly with the help of the stability charts mentioned previously, in which the dynamic stability of the helicopter is characterised by the oscillation period T_0 and the times T_D, T_H, in which the amplitude is doubled or halved, as the case may be. Let us take the single rotor helicopter as an example, because the conditions for this type are particularly simple, but of course similar calculations can be made for any other configuration.

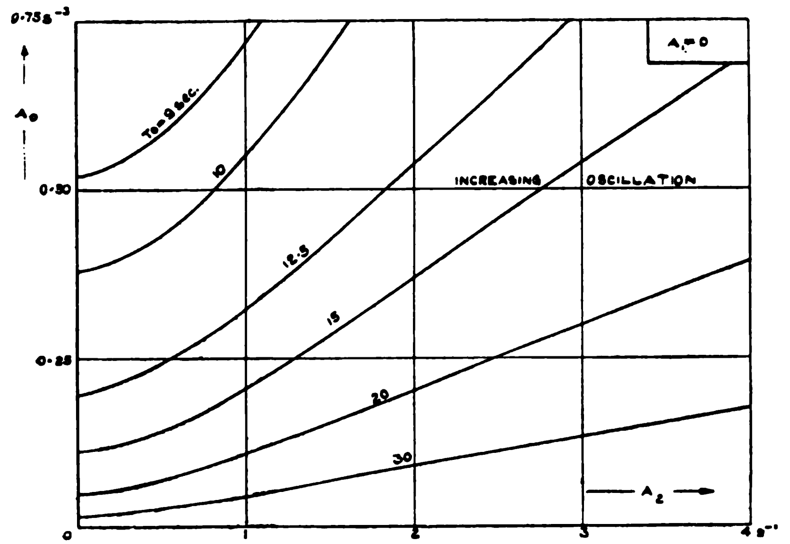
For the longitudinal motion of the Sikorsky R-4B with the controls fixed,

$$A_0 = 0{\cdot}1 \text{ sec.}^{-3} \text{ (approx.)}$$
$$A_2 = 0{\cdot}2 \text{ sec.}^{-1} \text{ (approx.)}$$

and thus we obtain from Figs. 2 and 3

$$T_0 = 16 \text{ sec. and } T_D = 5 \text{ sec.}$$

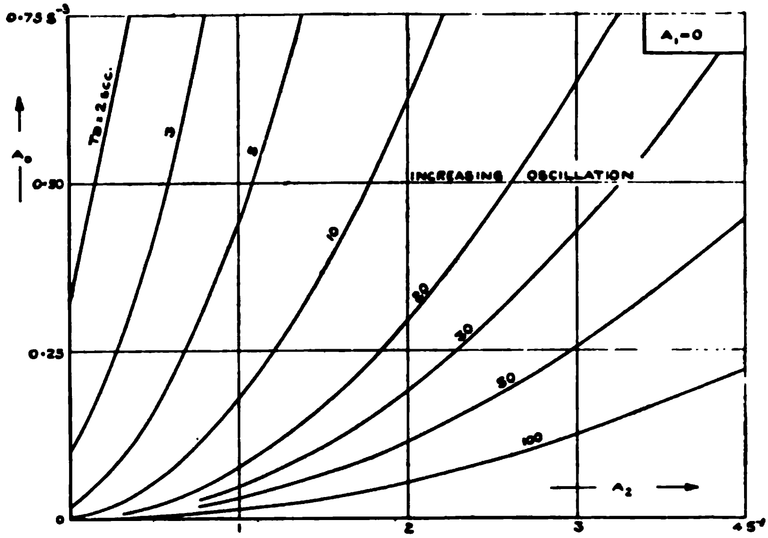
or, in other words, the helicopter is unstable and has a period of 16 sec. The amplitude of a disturbance is doubled in 5 sec. As already mentioned, the control displacements proportional to and in phase with the angular velocity of the helicopter have the effect of an apparent increase in the quantity A_2. It follows from Figs. 2 and 3 that both the period of oscillation T_0 and the time T_D become greater. The helicopter certainly becomes less unstable, but still remains unstable. In this respect the control displacements in phase with the angular velocity have the same effect as an increase of the blade masses. In the most favourable case (infinite control displacements) the oscillation becomes neutral. The reason for this perhaps astonishing fact is that we cannot apply pure moments about the longitudinal or lateral axis of the helicopter. With the present types of rotor control (tilting of the lift vector) the moments are always coupled with horizontal forces.



PERIOD OF OSCILLATION FOR $A_1 = 0$

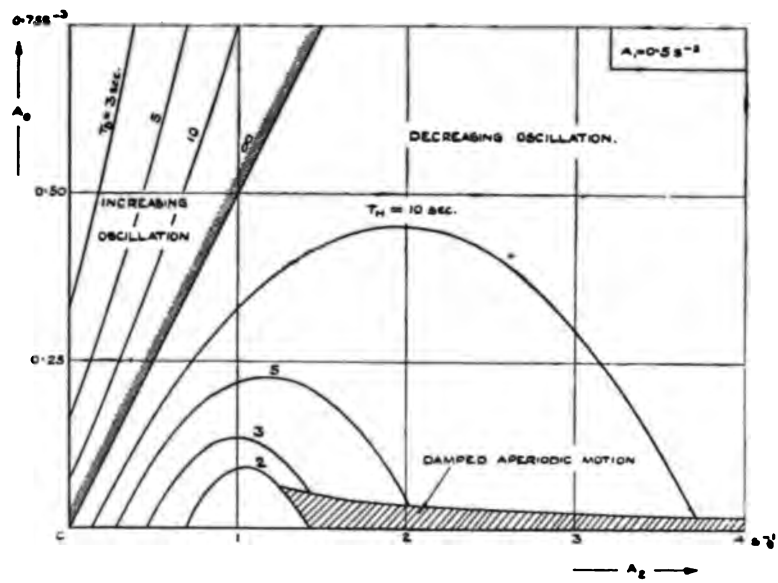
FIG. 2

If we have periodic control displacements in phase with the attitude, the stability chart is divided into a stable and unstable range, where the stability boundary is given by a straight line with the slope A_1 passing through the origin. The range above this boundary line corresponds to an unstable helicopter and below it to a stable one. In the stability charts of Figs. 4 and 5, $A_1 = 0{\cdot}5$. For the Sikorsky R-4B it means that the control displacements in phase with the attitude amount to approximately 10% of the attitude.



TIME TO DOUBLE AMPLITUDE FOR A_1=O.

FIG. 3



TIME TO DOUBLE (HALF) AMPLITUDE FOR A_1=O·5s^{-2}

FIG. 4

According to the investigations made up to the present this range appears to be the most promising for obtaining the best results.

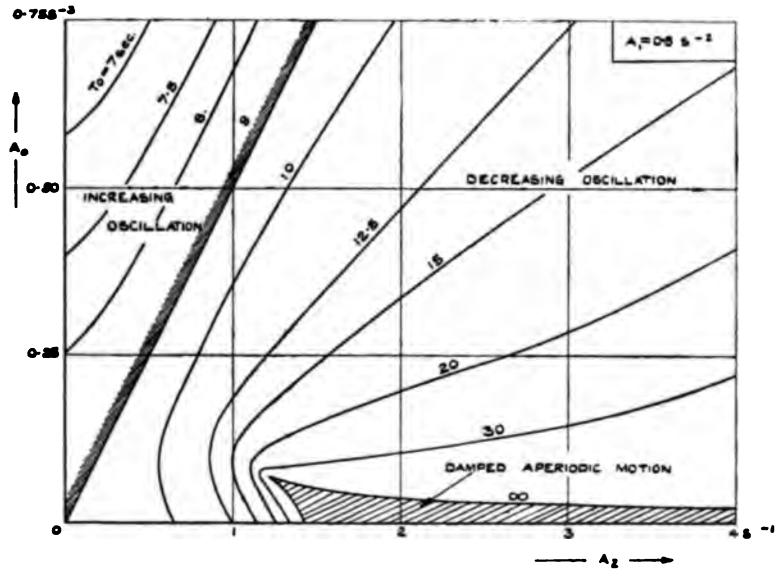
If we apply Figs. 4 and 5 to the Sikorsky R-4B we obtain for $A_0 = 0{\cdot}1$ and $A_2 = 0{\cdot}2$ a period of oscillation of 9 sec. As the above figures lie just on the boundary line, the helicopter is neutral. However, the dynamic stability can be considerably improved, if we apply additional control displacements in phase with the angular velocity, *i.e.*, if we increase the quantity A_2.

$$\text{For } A_0 = 0{\cdot}1 \text{ sec.}^{-3}$$
$$A_1 = 0{\cdot}5 \text{ sec.}^{-2}$$
$$A_2 = 0{\cdot}7 \text{ sec.}^{-1}$$

we obtain, for instance, from Figs. 4 and 5

$$T_0 = 11 \text{ sec. and } T_H = 3 \text{ sec.}$$

This means that a disturbance is halved in 3 sec. and we have a very effective automatic stabilisation.



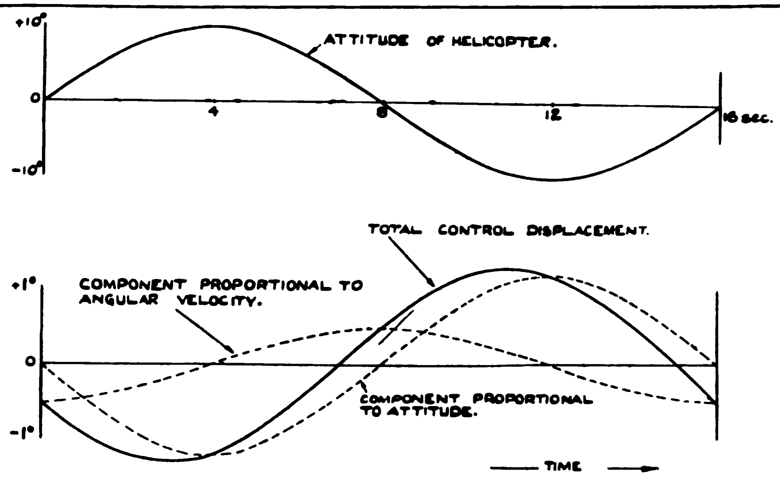
PERIOD OF OSCILLATION FOR $A_1 = 0{\cdot}5\,s^{-2}$

FIG. 5

It can be shown that the apparent change of the coefficients A_0, A_1, A_2 of the Sikorsky R-4B from $A_0 = 0{\cdot}1 \quad A_1 = 0 \quad A_2 = 0{\cdot}2$ to $A_0 = 0{\cdot}1 \quad A_1 = 0{\cdot}5 \quad A_2 = 0{\cdot}7$ requires an autopilot, the control displacements of which are approximately

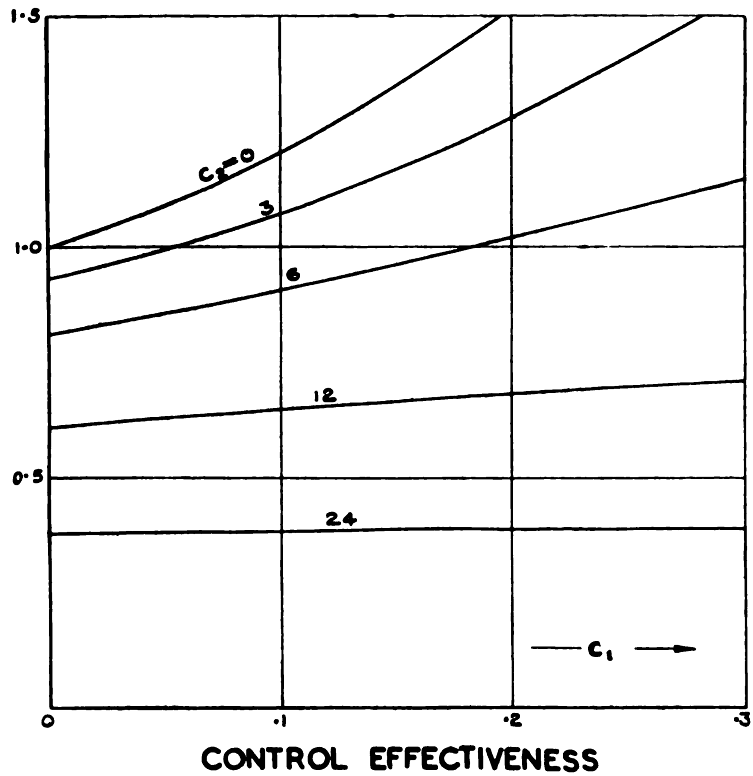
$$-\left(0{\cdot}12\alpha + 3{\cdot}25\,\frac{\dot{\alpha}}{\Omega}\right) \text{ rad.}$$

where α, $\dot{\alpha}$ denote the attitude and angular velocity of the helicopter, and Ω the angular velocity of the rotor. With an amplitude of $\alpha = \pm 10°$ and a rotor velocity of $\Omega = 25$ rad./sec. this hypothetical autopilot would apply the control displacements as given in Fig. 6.



CONTROL DISPLACEMENT DIAGRAM(C_1 = 0·12, C_2 = 3·25)

FIG. 6



CONTROL EFFECTIVENESS

FIG. 7

I would like to refer to two important facts at this point. Fig. 5 shows that the stability again decreases if the control displacement proportional to and in phase with the angular velocity of the helicopter becomes too large. We shall see later that the unsatisfactory stabilisation of the Bell and Hiller systems are probably due to this kind of "overcontrol" which is always coupled with long oscillation periods.

The other point is the control sensitivity, or, more accurately expressed, the response of the automatically stabilised helicopter to the pilot's control. According to J. STUART[2] we assume that the pilot applies manual periodic control displacement with a period of 4 sec. These manual control displacements impose on the helicopter forced oscillations of the same frequency, and the control sensitivity is defined as the ratio of the amplitude of forced oscillation of the helicopter to the amplitude of manual control displacement. For simplicity we will also assume that the helicopter is pivoted at its C.G., which means that only angular oscillations can occur. Our hypothetical autopilot may achieve automatic control displacements such as

$$-(C_1\alpha + C_2\frac{\dot{\alpha}}{\Omega}) \text{ rad.}$$

and we wish to know the effect of the quantities C_1, C_2 on the control sensitivity. The answer (for the longitudinal motion of the Sikorsky R-4B) is given in Fig. 7. The curves show the ratio of the amplitude of the helicopter with autopilot to the amplitude of the helicopter without autopilot, and thus give an idea of the effect of the automatic stabilisation on the control sensitivity. It follows that within the range of practical significance, C_1 has only a small influence. Large values of C_2, however, decrease the sensitivity. This means that too large automatic control displacements in phase with the angular velocity of the helicopter spoil both the dynamic stability and the control sensitivity.

BELL'S STABILISER AND HILLER'S SERVO CONTROL.

I assume that the stabiliser of the Bell helicopter is fairly well-known to my listeners ; therefore I shall confine myself to a brief summary of this device (Fig. 8).

The lifting rotor has two blades which are rigidly connected with each other and are attached to the rotor shaft by means of a universal joint. The feature of the Bell stabiliser is a bar with a mass on each end which rotates with the rotor. The bar is joined to the rotor shaft in such a way that it may pivot up and down ; this see-saw motion is provided with viscous damping. By means of a lever the bar is mechanically linked to the rotor in such a way that the displacement of the bar changes the pitch setting of the main blades. If, for instance, mass I rises, the pitch angle of blade I increases. As the two rotor blades are rigidly connected with each other, the pitch setting of blade II simultaneously decreases.

How does this device work ? In the undisturbed condition the centrifugal forces tend to keep the bar in its equilibrium position (plane perpendicular to the rotor axis) in which the pitch setting of the rotor is not affected.

If, however, the hovering condition is disturbed, *i.e.*, if a pitching or rolling motion occurs, the bar oscillates with the rotor frequency about its pivot. These oscillations are excited by the gyroscopic couple of the masses of the bar. The oscillations impose on the blades a cyclical pitch which means that an automatic control is applied. Automatic stabilisation can be achieved by using a proper layout. The main parameters in this respect are the viscous damping of the bar and the linkage ratio between the bar and the main rotor.

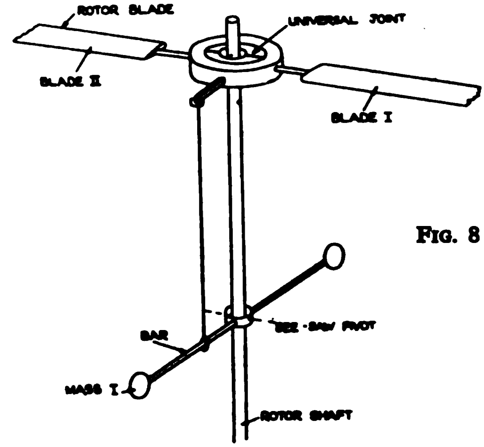


FIG. 8

BELL - STABILISER

Another automatic control device appeared recently. This is the control system of the Hiller helicopter. The fundamental idea is the same : automatic control by means of the gyroscopic couple and the restraining moment of centrifugal forces of masses rotating with the rotor. The most striking difference is that the bar has been replaced by servo blades, *i.e.*, the viscous damping has been replaced by the damping of the airforces. Another feature of the Hiller system is that the flapping motion of the main blades may be coupled with the pitch setting of the servo blades. It can be proved that this " feedback " has the effect of

(1) an apparent change of the damping of the servo-blades and

(2) an apparent increase of the disturbance of the helicopter.

The latter effect is almost identical with an apparent change of the linkage ratio between servo blade and rotor. This means that the two control devices are very similar with respect to the *automatic* control and may therefore be dealt with together. For simplicity we investigate the Bell stabiliser ; the basic results, however, can also be applied directly to the Hiller servo control.

Before going into the control device in connection with the stability of the helicopter, we first investigate the control displacements which occur if a rotor with Bell stabiliser is subjected to an angular oscillation with constant amplitude. Mathematically expressed, we will try to make a statement on the magnitude of the quantities C_1 and C_2 for a given period of oscillation. The answer is given in Fig. 9 where, following B. KELLEY[1], the amount of viscous damping is expressed as the "following time" T_f, in which a displacement of the bar is reduced to a tenth of its initial value. T_f is inversely proportional to the damping, and it means that a large value of T_f corresponds to a small damping and *vice versa*. The curves of Fig. 9 show the quantities C_1 (full lines) and C_2 (broken lines) for the linkage ratio n ($=$ 1·0) and a rotor angular velocity of $\Omega = 25$ rad./sec. against damping with the period of the enforced oscillation T_0 as parameter. The graphs have been plotted for $T_0 = 10$, 20 and 40 sec. ; they allow the following statements, which have a general application :—

(1) $C_1 = 1$ for zero damping ($T_f = \infty$) and decreases rapidly with increased damping.

(2) $C_2 = 0$ for zero damping and has a maximum at $T_f = 0{\cdot}366 T_0$. In the range of greater damping (*i.e.*, $T_f < 1$ *sec.*) C_2 is independent of the period of oscillation T_0.

(3) In the medium range, where both C_1 and C_2 occur, the control characteristics depend to a great extent on the period of oscillation : C_1 decreases and C_2 increases with increased period of oscillation T_0 and *vice versa*.

The automatic stabilisation of the helicopter requires both control displacements in phase with the attitude and in phase with the angular velocity of the helicopter ; we are therefore forced to choose a small damping of the bar. In this range C_1 and C_2 are greatly affected by the period of oscillation. We have seen previously (Fig. 4) that large control displacements in phase with the angular velocity of the helicopter increase the period of oscillation. On the other hand, Fig. 9 shows that long periods of oscillation increase the control displacements in phase with the angular velocity of the helicopter. It must therefore be suspected that the Bell stabiliser tends to increase the period of oscillation to such an extent that only an unsatisfactory stabilistion is achieved and such proves to be the case in actual fact (Fig. 10). The curves are calculated for the longitudinal motion of the Sikorsky R-4B fitted with a Bell stabiliser, where, according to B. KELLEY, a following time of $T_f = 3$ sec. has been assumed. The graphs are plotted against the linkage ratio

$$n = (\text{change of pitch setting of main blade})/(\text{displacement of the bar})$$

and show that in the most favourable case ($n = 0{\cdot}3$) a very slightly damped oscillation with a period of 26·5 sec. occurs. The amplitude is halved in 37 sec., which means that the longitudinal motion is almost neutral. When $n < 0{\cdot}16$ the helicopter becomes unstable, *i.e.*, in the stability charts (Figs. 4 and 5) the helicopter goes over from the stable to the unstable range when the A_2 value is too small. Summing up, we can say that the Bell stabiliser counteracts the inherent instability of the helicopter, but the results are not yet up to expectations.

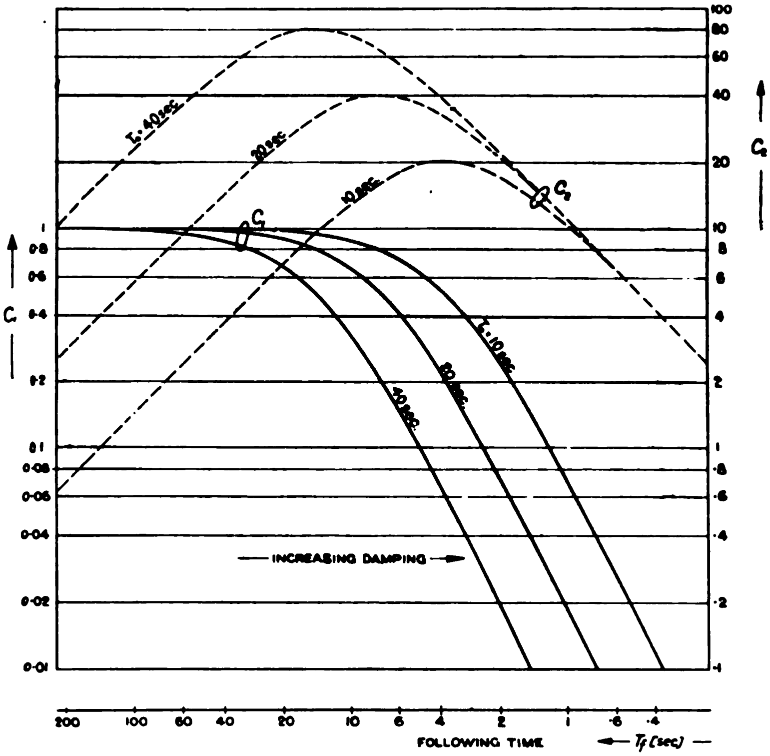
I would like to mention that the curves of Fig. 9 may also be applied directly to the flapping motion of the rotor blade for the case in which the rotor is subjected to oscillations with constant amplitude. The " following time " T_f of the rotor blade is given by

$$T_f = \frac{40}{\gamma\Omega} \text{ sec.}$$

where γ denotes the inertia number of the blade and Ω the angular velocity of the rotor. It can be shown that the coefficients a_1, b_1 of the flapping angle β ($\beta = a_0 - a_1 \cos\psi - b_1 \sin\psi$) can be divided into components in phase with the attitude, and with the angular velocity of the helicopter. The coefficient a_1, for instance, may be expressed as

$$a_1 = -(C_1 a + C_2 \frac{\dot{a}}{\Omega})$$

For the blade of the Sikorsky R-4B the following time T_f amounts to approx. 0·13 sec. The graphs of Fig. 9 (the curves may also be applied in approxi-



CONTROL DISPLACEMENTS OF BELL STABILISER

FIG. 9

mation to an increasing or decreasing oscillation) show that for this degree of damping, $C_1 = 0$; which means that the flapping motion is proportional to the angular velocity of the helicopter and may therefore be considered as a sequence of steady conditions. However, the flapping motion in phase

with the attitude of the helicopter can no longer be neglected if short oscillation periods occur. The basic parameter in this respect is the frequency ratio, (circular frequency of the oscillation of the helicopter)/(angular velocity of the rotor). It can be proved that the stabilising effect credited to the downwash lag (Strahlablenkungs-Effekt) is partly due to the static stability caused by the flapping motion in phase with the attitude of the helicopter. Therefore, the results of model tests with oscillating rotors may only be applied to the full scale helicopter if the frequency ratio just mentioned is the same.

How Can the Present Control Devices be Improved?

To be able to improve the Bell and Hiller systems we must first know what is still wrong with them. Our example has shown that with a following time of $T_f = 3$ sec., a disturbance of the longitudinal motion of the Sikorsky R-4B is, in the most favourable case ($n = 0{\cdot}3$) halved in 37 sec., where a period of oscillation $T_0 = 26{\cdot}5$ sec. occurs. It can be seen from Fig. 9 that for $T_f = 3$ sec. $T_0 = 26{\cdot}5$ sec. and $n = 0{\cdot}3$, $C_1 = 0{\cdot}03$ and $C_2 = 9$, which means that the Bell stabiliser in this case has about the same effect as a hypothetical autopilot, the control displacements of which are

$$-(0{\cdot}03\alpha + 9\frac{\dot{\alpha}}{\Omega}) \text{ rad.}$$

We have previously seen that an autopilot with the control characteristics $C_1 = 0{\cdot}12$ and $C_2 = 3{\cdot}25$ results in a very effective stabilisation (Table 1). By comparison of the two pairs of values, C_1 and C_2, it follows that

(1) the quantity C_1 of the Bell stabiliser is too small and must therefore be increased, and

(2) the quantity C_2 is too large and must therefore be decreased.

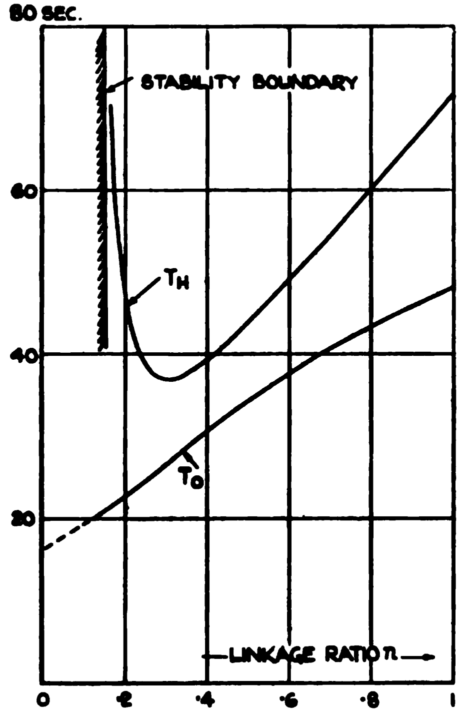
How can it be managed? Fig. 9 shows that the desired changes occur if the period of oscillation decreases. On the other hand, we see from Fig. 4 that this decrease of the period of oscillation can be attained by a decrease of the coefficient A_2 of the frequency equation, *i.e.*, by counteracting control

TABLE I.

LONGITUDINAL MOTION OF SIKORSKY R-4B.

	Without control device	*With autopilot*	*With Bell Stabiliser* $T_f = 3$ sec., $n = 0{\cdot}3$
	UNSTABLE	STABLE	NEUTRALLY STABLE
C_1	0	0·12	0·03
C_2	0	3·25	9·0
T_0	16 sec.	11 sec.	26·5 sec.
T_D, T_H	$T_D = 5$ sec.	$T_H = 3$ sec.	$T_H = 37$ sec.

displacements in phase with the angular velocity, or, more generally expressed, by a decrease of the damping of the helicopter. This can be done by various means. It could, for instance, be accomplished by a counteracting second bar (*Provisional Specification 14988/48 of 3.6.1948*) which has such a degree of damping that only control displacements in phase with the angular velocity



INFLUENCE OF BELL STABILISER ON SIKORSKY R-4B

FIG. 10

of the helicopter occur. The basic idea is illustrated in Fig. 11. The two differently damped bars rotate with the rotor and are connected to the rotor by a system of linkages in such a way that the change of pitch-setting of the rotor blades is

$$n_1\delta_1 + n_2\delta_2$$

where n_1, n_2 denote the linkage ratios and δ_1, δ_2 the angular displacements of the two bars. In our example the quantities n_1, n_2 must have opposite signs, which means that the heavily damped second bar counteracts the excessive control displacements in phase with the angular velocity of the helicopter achieved by the slightly-damped first bar.

As an example, calculations for the longitudinal motion of a Sikorsky R-4B fitted with a double bar stabiliser have been carried out (Fig. 12). The curves are plotted against the linkage ratio n_2 of the second bar and show for the two modes of oscillation, the times T_H in which a disturbance of the automatically stabilised helicopter is halved. In this example

First bar :	*Second bar* :
$T_{f1} = 3$ sec.	$T_{f2} = 0{\cdot}46$ sec.
$n_1 = 0{\cdot}25$	

This means that the first bar has the same degree of damping as in the

previous example of the Bell stabiliser. If $n_2 = 0$ the second bar is put out of action and, in agreement with the previous investigation, a disturbance is halved in approx. 40 sec. Besides this mode of oscillation, a heavily damped short period oscillation occurs ; this mode of oscillation generally has very little practical significance and has therefore not been mentioned until now. It can be seen from Fig. 12 that the second bar affects the two modes of oscillation in such a way that

(1) the originally slightly damped oscillation becomes more stable, and
(2) the originally heavily damped oscillation becomes less stable.

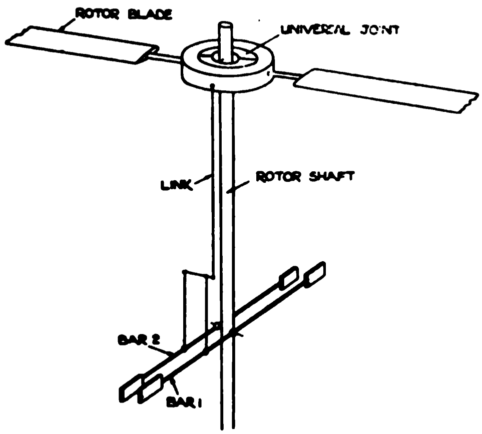
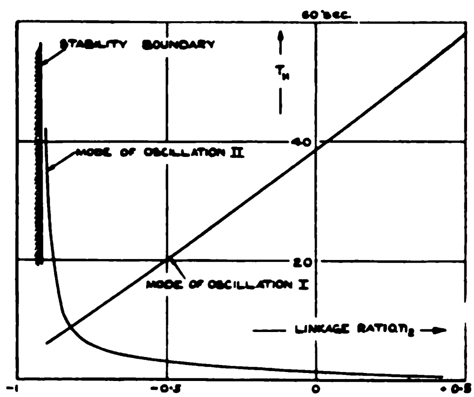


FIG. 11

DOUBLE BAR STABILISER

FIG. 12



INFLUENCE OF DOUBLE BAR STABILISER ON SIKORSKY R-4B

The stability boundary is given by $n_2 = -0{\cdot}92$. The optimum lies at or near the point of intersection of the two curves ($n_2 = -0{\cdot}82$) where the amplitude of both modes of oscillation is halved in approx. 8 sec. The optimum value found for the Bell stabiliser was 37 sec. We thus attain

a considerable improvement in stability, which in theory can be improved still further by using other combinations of the damping of the two bars.

However, I would like to make it perfectly clear that at present we are dealing with purely theoretical investigations, and that their accuracy and practical applications have still to be confirmed by tests.

Conclusions.

In conclusion I wish to summarise the essential facts once again. The control displacements necessary to govern an unstable helicopter may be divided into displacements which are proportional to and in phase with the attitude and the angular velocity of the helicopter respectively. The former correspond to a kind of static stability and the latter to a damping of the pitching or rolling motion. It appears that any helicopter can be stabilised by a proper combination of these two types of control displacements.

For the Sikorsky configuration some noteworthy statements can be made. In the ideal case where there is no time lag in the control device and in the flapping motion of the blades, control displacements proportional to and in phase with the angular velocity of the helicopter alone are not sufficient to stabilise the single rotor helicopter. The reason for this perhaps astonishing fact is that we cannot impose a pure pitching or rolling moment. With the present systems of rotor control (tilt of the lift vector) the moments are always coupled with horizontal forces. Effective stabilisation of the Sikorsky configuration requires a certain combination of the two types of control displacements. The stability again decreases if too large control displacements in phase with the angular velocity of the helicopter are applied.

Contrary to fixed-wing aircraft where the automatic control and stabilisation require the installation of a special gyroscope, the helicopter can make use of its rotor, which is in itself a gyroscope. Examples of this group are the Bell stabiliser and the Hiller servo rotor. It is obvious that automatic stabilisation can be achieved by using a proper layout. The results, however, are not yet up to expectations. The present gyratory stabilising systems require a compromise which is usually such that the control displacements in phase with the angular velocity of the helicopter are too large in relation to those in phase with the attitude. This kind of automatic " overcontrol " spoils both the dynamic stability and the response to the pilot's control. It is to be expected that within the next few years some more control devices will appear and that the present state of automatic stabilisation will be considerably improved.

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DISCUSSION.

MR. J. S. SHAPIRO (Founder Member): There are many people who doubt the necessity for developing a stable helicopter and I would like to hear the views of the department for which DR. SISSINGH works, on the subject. Personally, I have no doubt at all, that a stable helicopter is essential for widespread private ownership, and a great help for commercial operation.

Stability is measured by two parameters, being the natural period and the damping factor of the oscillation of the machine. I would like to know, whether, in the light of the department's flying experience, they have specific views on desirable values for either parameter and whether they know to which of the two the Pilot is more sensitive.

In the paper DR. SISSINGH mentions a criterion of control sensitivity, being a ratio of machine amplitude to control amplitude in forced oscillatory motions of the helicopter; our own method of judging control sensitivity is by means of the ratio between the moment produced by unit displacement of control to the moment of inertia of the machine, in other words, the angular acceleration imposed by unit displacement of control. I am wondering whether the lecturer's criterion is more significant than our own, especially as it is bound to be a function of frequency of oscillation.

I would also like to add another question referring to the hypothetical 'autopilot' namely, the effectiveness of automatic control displacements proportional to the angular acceleration of the machine.

MR. R. HAFNER (Member): I believe that there is a need for positive stability in forward flight, but one might perhaps be satisfied in hovering with only a neutrally stable rotor. I would like to point out that the stability cubic in DR. SISSINGH's paper applied to two dimensional movement and the coupling between the longitudinal and lateral motion has been ignored.

I would also like to point out that the lack of stability in a hovering helicopter can be clearly recognised even during very small displacements of the aircraft. It is quite clear, however, that the minute translational velocities caused by such movements are much too small to produce a significant flapping motion of the blade, if indeed friction in the flapping hinges and similar marginal factors do not entirely overshadow this effect. I am of the opinion therefore, that some of the fundamental reasoning in conventional stability calculations breaks down in practice for very small movements and the instability observed then is symptomatic not so much of the mechanical features of the rotor (blade flapping, etc.) as of an aerodynamic feature connected with the slipstream. We know that a fast climbing rotor or auto-rotating rotor is more stable than a hovering rotor or indeed one operating in the vortex ring state. I had hoped to learn more about this aerodynamic derivative. In fact, what is the stability of an actuator disc carrying a weight underneath?

DR. J. A. J. BENNETT (Founder Member): It would appear that the helicopter is dynamically unstable so long as the tip-path plane oscillates in phase with, and with the same amplitude as, the body of the aircraft. We have two extreme cases to consider, therefore. The case of the tip-path plane oscillating with the same amplitude as the body of the aircraft is more or less typical of existing helicopters and, if the rotor were subject to complete

gyroscopic control, the tip-path plane would remain stationary as the body of the aircraft oscillates. The stabilising device must control the tip-path so that its oscillation is only partly suppressed.

Although in his analysis DR. SISSINGH has assumed that the rolling and pitching oscillations of the helicopter are independent, has he considered the cases in which the undamped natural frequency of the flapping motion is not equal to the angular speed of the rotor, *i.e.*, the effect of " delta three " or flapping hinge offset. If an offset of the flapping hinge can give dynamic stability, are the best results obtained with a positive or negative offset?

MR. A. MCCLEMENTS (Founder Member): The lecturer has today considered the case of the single rotor helicopter. In view of the possibility of multi-rotor machines becoming available, I would like to enquire if DR. SISSINGH can advise us if the stability of the multi-rotor configuration is likely to present less of a stability problem than the single rotor machine. Also, is anything known about which multi-rotor arrangement is best from the stability viewpoint?

MR. D. R. GARRAWAY (Member): The amount of damping applied to the stabilising bar can be adjusted to give the best response to lateral oscillation, but since the inertia of the helicopter is less in roll than pitch, the stability characteristics in a lateral sense will not be as satisfactory as if the damping were selected for optimum lateral stability. In a typical aircraft having optimum longitudinal characteristics how do the resulting lateral characteristics compare with the optimum ones?

DR. THURSTON (Member): I would like to point out that from experiments which I have made it is possible to stabilise blades in a similar way to ordinary aircraft, and that the problem of stability of helicopters is very similar to the problem in fullsize aircraft, and its solution appears to be following on the same lines.

Many years ago I constructed helicopter blades which were stabilised by elevators and fins, and I feel that a great deal of experimental work could be done with the use of models in this respect.

MR. W. STEWART (Member): I would like to offer a few comments in reply to several speakers, who have raised questions on the wider implications of DR. SISSINGH's lecture and on possible alternative solutions.

As Mr. Shapiro has pointed out, the stability characteristics of the helicopter—as of the fixed-wing aeroplane—go beyond the stick-fixed motion discussed by DR. SISSINGH. In fact, it can be divided into four classes, *viz*: the static and dynamic stability under stick fixed and stick free conditions, the lecturer having dealt with only one of these. The pilots' impressions of the flying characteristics are a combination of these together with control response and effectiveness. It is agreed that the most important influence is the stick-free conditions. However, to consider the desirable handling qualities of a helicopter would require a complete lecture on this subject.

Dr. Sissingh's work has shown the control displacements required to stabilise the helicopter motion and has indicated the influence of automatic devices applying these displacements under stick-fixed conditions. Never-

theless, the work could be applied in a different form to stick-free considerations. An important point—perhaps not sufficiently emphasised by Dr. Sissingh—is that most automatic devices improve stability at the cost of loss in the pilot's control effectiveness. Dr. Sissingh's method involves only a small loss of control effectiveness for the stability gain.

The control sensitivity used by Dr. Sissingh, *i.e.*, the control displacements to produce a constant amplitude oscillation of a given frequency, is not a good handling criterion but it constitutes a very good method of mathematical treatment. It is fully appreciated—and I thoroughly agree with Mr. Shapiro—that neither this method not the more usual response to unit control method are satisfactory ; but I have no better criterion to offer as yet.

Mr. Fitzwilliams has mentioned the possible solution advocated by Professor Miller. This is sound in theory but would be difficult to design in practice. It would be exceptionally difficult to arrange for the appropriate twisting of the blades to provide the cyclic changes required. The use of stiff blades with a spring support may well give rise to undesirable blade oscillations and may even lead to flutter.

I agree with Mr. Hafner that the double bar is a considerable complication to ask of the designer. The simple offset hinge does affect stability but the improvements possible are very small. For most blades a negative hinge offset is required but for very heavy blades positive offsets can give a little improvement. Again, vibration must be considered.

In reply to Dr. Thurston, the use of auxiliary aerofoils to stabilise each of the blades (and to control them) has been tried. The Landgraf system could be considered as a step in this direction but there is a system with the auxiliary blades several chord lengths behind the main blades. However, while it would appear that this stabilises the blade motion and to a much lesser extent the helicopter, very little information is available. Vibration trouble due to possible dissymetry between each blade system should be considered.

Dr. Sissingh's reply to the Discussion.

In reply to Mr. Shapiro. In the future the helicopter will probably be engaged in a silent but tough fight for general recognition by the public. In my opinion an effective automatic control device which stabilizes the helicopter without too much loss of control sensitivity would be a very valuable contribution towards making the public helicopter-minded and increasing the applications of helicopters. I fully agree with Mr. Shapiro that dynamic stability is one of the essentials for widespread private ownership. From the point of view of stability an aperiodic subsidence of the disturbance would probably be desirable. However, this requires such a degree of damping in pitch and roll that the response to the pilot's control becomes insufficient. This means that a compromise must be found ; the final decision is left to the pilot, but owing to lack of practical experience it is not yet possible to make any forecasts in this respect. It may be assumed, however, that very short oscillation periods are undesirable, and it is my personal belief that with present knowledge the solution of the stick-fixed stability is easier than that of the stick-free stability.

As already stated by Mr. STEWART, the criterion for control effectiveness mentioned in my paper is characterized by a simple mathematical treatment. The control period of 4 secs. is taken from the paper by J. STUART and corresponds to average practical conditions. I admit that this criterion is by no means ideal, and if, in spite of this, I have mentioned that criterion, it has been done to show in a simple way that the loss in control sensitivity is mainly caused by the control displacements proportional to the rate of change of attitude. The criterion mentioned by Mr. SHAPIRO only covers the initial acceleration. Actually, what we want to know is how quickly, to what extent, and in what way (with or without overshoot) the helicopter responds to the control. Unfortunately, neither of these criteria can give the answer to these questions. I would like to take this opportunity of referring to a paper by R. H. MILLER (*Journal of the Aeronautical Sciences*, August, 1948) dealing with automatic control and response of the automatically stabilized helicopter to the pilot's control, which appeared after I had completed my manuscript.

With regard to the control displacements proportional to the angular acceleration, it should be noted that, although the vector of the angular acceleration in an undamped oscillation has a phase difference of 180° in comparison with the attitude vector, the effect of these control displacements is quite different from that of the control displacements proportional to the attitude. If we apply control displacements proportional to the angular acceleration in the Sikorsky configuration, then it is only the factor of λ^3 which is changed in the frequency equation of the 3rd order ; the other coefficients remain unchanged. Particular attention should be paid to the fact that the coefficient of λ remains zero, *i.e.*, dynamic stability cannot be obtained in this way. In the most favourable case the coefficient of λ^3 becomes zero, which means that the helicopter is neutral. The control displacements proportional to the angular acceleration have a certain similarity to an apparent change of the moment of inertia of the helicopter. The difference lies in the fact that a change of the moment of inertia only affects the equilibrium of the moments, while the control displacements proportional to the angular acceleration also affect the equilibrium of the horizontal forces as well.

In view of Prof. MILLER's suggested solution I should like to add the following remarks on the statement by Mr. STEWART : I presume that Prof. MILLER's arrangement corresponds to a hypothetical autopilot which responds with a small time lag to the angular velocity of the helicopter. This time lag has the effect that one component of the control displacement is in phase with the attitude, *i.e.*, automatic stabilization is possible under certain conditions. However, here again we probably have the disadvantage that the control displacements proportional to the rate of change of attitude are too large in comparison with those proportional to the attitude. This would mean that very slightly damped oscillations with long periods of oscillation occur.

I agree with Mr. HAFNER that for the Sikorsky configuration the coupling between the longitudinal and lateral motion is very important. For simplicity, this coupling has been neglected in my paper, and this means I have assumed that the hypothetical autopilot

(1) applies the required longitudinal control displacements, and

(2) compensates the lateral tilt of the lift vector of the rotor at all times.

The investigations have shown that these effects can to a certain extent be accomplished by various means, so that in the first approximation the simplification is justified.

If the hovering state is disturbed, we have a flapping motion of the blades due to both the angular and linear velocity of the helicopter. Theoretically, the two components are approximately of the same order of magnitude. As measurements on the flapping motion in the disturbed hovering state are not known, it is very difficult to make any statements on the influence of the friction in the flapping hinges. I personally believe that this effect may be neglected. As far as I know, the theoretical investigations on the hovering stability compare fairly well with flight measurements. The main causes of discrepancies are probably the twisting of the blade, play in the controls and—if the stick is not actually clamped—the involuntary control displacements of the pilot.

It is known that in the hovering state near the ground and in vertical descent, the slipstream changes the rotor derivatives and, through this, greatly affects the stability. Unfortunately, the existing measurements are not adequate to make further detailed statements in this respect. With regard to the stability of an actuator disc carrying a weight underneath ; if the actuator disc is defined as a hypothetical device, the resulting force of which is always perpendicular to the disc and passes through the centre, the motion is neutral.

In reply to Dr. BENNETT. If we neglect the flapping of the blade due to the linear and angular velocity of the helicopter, the tip path plane of a helicopter with the controls fixed oscillates in phase, and with the same amplitude as the body of the aircraft. If the control displacement is equal to the attitude ($C_1 = 1$), the lift vector of the rotor always remains approximately vertical. In the case of an automatically stabilized helicopter the tip path plane oscillates with a time lag and with a smaller amplitude when compared with the oscillation of the fuselage.

Take the case where the undamped natural frequency of the flapping motion is not equal to the angular speed of the rotor : if a helicopter is subjected to pitching oscillations we have an oscillation of the lift vector in two directions, longitudinal and lateral. Both modes of oscillation can split up into components in phase with the attitude and the angular velocity of the pitching motion. Any device or arrangement which influences the undamped natural frequency of the blade effects a change of the oscillations of the lift vector. By using a proper layout this effect can be employed to decouple the longitudinal and lateral motion of the single rotor helicopter to a considerable extent.

Regarding the effect of the offset of the flapping hinges, I would like to add the following statement to the remarks by Mr. STEWART : For the Sikorsky configuration with the controls fixed it follows that a positive hinge offset has approximately the same effect as an increase of the distance of the rotor above the *C.G.* of the helicopter and *vice-versa*. This means that the coefficients A_0, A_2 of the frequency equation are multiplied by a factor

>1 in the case of a positive hinge offset and by a factor <1 in the case of a negative hinge offset. In the stability charts (Figs. 2, 3), this change of the hinge offset has the effect of moving along a straight line passing through the origin with the slope A_0/A_2. An increasing positive hinge offset means that we move to the right and an increasing negative offset means a move to the left. It follows that the stability is improved by a positive offset if the slope of the T_D—curve in Fig. 3 is larger than A_0/A_2, and by a negative offset if the slope is smaller than this figure. However, as the coefficient A_1 remains zero, the motion always remains unstable.

Replying to Mr. McClements. Due to increased damping multi-rotor helicopters are generally less unstable than single rotor helicopters. With a proper layout it is possible to fulfil Routh's stability criterion under certain conditions, but even in this case the damping of the disturbed longitudinal or lateral motion is generally very small. A main parameter in this respect is the mutual inclination of the rotor axes. If we take the hovering stability of a tandem rotor helicopter as an example, it follows that the longitudinal motion has a certain similarity to an over-controlled single rotor helicopter, which means that slightly damped oscillations with long periods of oscillation occur. The lateral motion (if we neglect the coupling between these two motions) does not differ in principle from that of a single rotor helicopter.

At present very little is known about the interference of the different rotors in multi-rotor helicopters in forward flight. Therefore I am not in a position to formulate any statements about the best multi-rotor arrangement.

In reply to Mr. Garraway. With regard to the comparison of the longitudinal stability with the lateral stability, it can be stated that a decrease of the moment of inertia of the helicopter improves the stability. In the case of the Sikorsky configuration fitted with a hypothetical autopilot the coefficients A_0, A_1, A_2 of the frequency equation are inversely proportional to the moment of inertia. For the Sikorsky R-4B the moment of inertia in roll is about eight times less than that in pitch, which means that in the example in my paper (Sikorsky R-4B fitted with autopilot) the amplitude of the lateral motion is halved in 1.7 sec. instead of 3 sec. for the longitudinal motion. A similar improvement appears in the case of the Sikorsky R-4B fitted with a Bell stabilizer. It is seen that the longitudinal stability of a single rotor helicopter in hovering flight is a stronger criterion than the lateral stability and we do not need to worry about the rolling motion if the pitching motion is sufficiently damped.

In conclusion, and in reply to Dr. Thurston : To stabilize a helicopter we need certain control displacements proportional to the attitude and to the rate of change of attitude, or the corresponding flapping motion of the blades. It does not matter how this effect is brought about. Generally it will be done, directly or indirectly, by the gyroscopic couple of rotating masses. This mass may be a gyro, Bell stabilizer, Hiller servo blade, an auxiliary aerofoil attached to the blade or, as in the proposal of Prof. Miller, the blade itself. All devices mentioned above respond mainly to the angular velocity of the helicopter. The stability problem is solved if we succeed in producing a sufficient time lag, which means that a proper component of the control displacement (or of the flapping motion of the blades) proceeds in *phase* with the attitude of the helicopter.

Mr. Raoul Hafner's Vote of Thanks to Dr. Sissingh.

Mr. Chairman, Ladies and Gentlemen.

It is my pleasant task to express the appreciation of the members and guests of the Helicopter Association to Dr. Sissingh for having given us such an excellent paper, a paper which has helped his audience, to understand, without the aid of complicated mathematics, a most difficult problem. For myself, I believe that the two factors mainly involved in the stability of the helicopter are control displacements proportional to the attitude and control displacements proportional to the rate of change of attitude. Most schemes evolved for achieving stability do involve the use of these two separate variables but unfortunately do not permit fully their independent use and so have met with only partial success. I express the hope that the double bar system will bring us the stability for which everyone is seeking.

Finally I should like to congratulate Dr. Sissingh for without doubt one of the most excellent papers ever read before our Association, and propose a hearty vote of thanks to him, a vote of thanks which I am sure has the support of everyone here today.

London—Paris Helicopter Link.

As most members are probably aware a demonstration to prove the feasibility of the use of helicopters in restricted spaces was staged on the 30th September, 1948, by carrying a letter from the Lord Mayor of London to the President of the Conseil Municipal of Paris by air from city centre to city centre. Aircraft taking part in the demonstration were the 171 Helicopter (Bristol Aeroplane Company) from St. Paul's, London, to Biggin Hill Aerodrome ; the Meteor 7 (Gloster Aircraft Company), from Biggin Hill to Orly Aerodrome ; and the S.51 Helicopter (Westland Aircraft Company), from Orly Aerodrome to the Place des Invalides, Paris.

An Air Mail cover commemorating this occasion has been presented to the Association by Mr. N. J. G. Hill.

Acknowledgements.

The Council wish to record, on behalf of the Association, their very sincere appreciation of recent presentations in respect of the new office and library. These presentations are more than welcome to a young body such as ours.

In the first instance, thanks are due to one of our founder members, MR. NEIL MORRIS. From his Glasgow factory, which specializes in woodwork and rotor blades, he has presented the Association with a very handsome oak bookcase and cabinet. It is now in the office, housing the Association's technical and semi-technical library. A suitably inscribed plate is being prepared to record the presentation.

Appropriately enough we also have to acknowledge the presentation of a number of books to the library by another member, MR. C. C. COOPER, on his return to this country from a visit to the U.S.A. The library is now being reorganised and a list of the books available will be sent out to members in due course. MR. COOPER at the same time has also kindly presented the Association with a film he has taken of the latest Helicopter developments in the U.S.A. which it is hoped to show to members after the next meeting.

The World's Largest Helicopter

THE CIERVA "AIR HORSE," photographed during its first free flight on the 8th December, 1948, at Southampton, piloted by H. A. MARSH, A.F.C.

Crop Spraying in the British Empire

Two very interesting Reports have recently come to hand and are here placed on record, being the first applications by British operators of the Helicopter to agricultural use.

The reports are of a preliminary nature and cover few of the technical details, but are none the less interesting in their appreciation of the general problems of Tropical operation. Arrangements are in hand to organize a meeting of the Association to discuss the various aspects of crop spraying at which the operational and chemical problems may be examined in full.

FROM MESSRS. IRVIN-BELL HELICOPTER SALES, LTD.,

TRINIDAD. *July*, 1948.

An experiment in the use of the Helicopter for dusting sugar cane was recently made in Trinidad, British West Indies. The Helicopter used was a Bell 47D operated by Irvin-Bell Helicopter Sales Ltd., on behalf of Messrs. Caroni Ltd., and flown by Mr. N. J. CAPPER, A.F.C.

Messrs. Caroni, among other sugar growers in Trinidad, have been trying to find a satisfactory method of dealing with the froghopper, an insect pest which feeds on sugar cane, and in some areas causes considerable damage. Ground equipment has so far been found unsatisfactory, because of the expense involved and the difficulty of covering a large acreage.

The machine arrived in Trinidad on the 21st June, 1948. British West Indian Airways were more than generous in providing accommodation for its unloading and erection, and in giving assistance, and, on the 25th June it was flown from Piarco Airport to the Waterloo Estate of Caroni Ltd., where a special hangar had been built.

Some experiments were carried out from the 28th June until 1st July, in order to find out the best rate of application of the insecticide, the best height to fly, speed, etc. Then it was decided, as the froghopper which emerges during the rainy season had made an early appearance, to start dusting with a view to killing froghoppers and to make experiments during the process.

Between the 1st July and the 17th August some 3,000 acres were covered. Dusting was done in the early morning, evening and night. The froghopper is a night feeder and hides in the sugar cane during the day. It will only come out before dusk if the temperature drops, and it retires to the cane at about 7 a.m. The best results were obtained at night when the strength of the wind was usually less than 5 m.p.h.

Insecticides used were D.D.T., and "Gamexane," and it was soon found that the helicopter provided a means of applying insecticide far superior to any way which had been tried before.

In good conditions the adult froghopper could be eliminated, but unfortunately although the dust was forced right down through the cane by the down wash from the helicopter rotor, the residual effect of the insecticide was most disappointing and did apparently no damage to the "nymph" or grub. This meant that as the adult population would build up again in three or four days, repeat dustings had to be made. Nevertheless the population must have been reduced.

Dusting a sugar cane field.

The operations were carried out from Derrick Sites on the various Estates and fuel, dust, etc., were run to the site by the Company's " loco." The helicopter showed that it could land in places unfit for walking, or even horse-riding, but sites had to be chosen which permitted safe walking for the loading teams. Moonlight flying presented little difficulty, especially when the pilot was familiar with the field and obstructions. Without a headlight dusting in complete darkness is not considered practicable, as difficulty in seeing the top of the sugar cane and gauging height above it is experienced. Flights to and from the base were made in darkness without trouble.

Although temperature and humidity were high, the latter being 98 to 100% and the density altitude at times 2,700 feet, the Franklin engine gave full power and the Bell carried its full load of dust with 14 Imperial gallons of fuel. Dusting was carried out at cane top height at 20 m.p.h., and it was found that 60 to 70 acres could be covered in one hour's flying when dusting individual fields. Re-loading with dust took from half-a-minute to one minute when the crew were trained.

From the point of view of the Bell Helicopter the experiment was most successful as it showed its ability to apply insecticide evenly over a large area. Far better results could no doubt be obtained if more effective insecticides were used to eliminate the necessity of redusting frequently, as this necessity reduced the number of acres which can be covered in a season by one helicopter. From the pilot's point of view the experiment was intensely interesting. Dusting sugar cane in the Tropics by moonlight in a helicopter is an experience it must be difficult to surpass.

The machine proved itself in every way a real work horse. Tropical conditions with their heat, high humidity and torrential rain seemed of no account. The helicopter was housed almost on the doorstep of the bungalow occupied by the pilot and engineer and flights to the dusting areas were made in a few minutes. These flights provided a unique view of the natives' rice

growing activities, and the take-off attracted the usual audience. Landing sites needed no special preparation, the helicopter was just adapted to any conditions without trouble.

Practically all the cane fields were quite straight forward and without obstructions, but a few were surrounded and broken up by trees and hedges. None of these were refused and served to show that the helicopter can dust almost anywhere. Dusting runs were made across wind and all turns into wind. The perspex bubble was kept on as a protection against heavy rain, birds, etc., and even in the heat of the day the cockpit temperature was pleasantly cool as soon as the helicopter was airborne. Several small birds were hit with no damage to the rotor. The bigger birds kept well away and showed a preference for less animated material.

On Wednesday, the 14th July, the Governor of Trinidad, Sir JOHN SHAW, attended a demonstration at the Caroni Estate, after which he was flown from Caroni Estate to Government House, and landed on the lawn in Government House grounds.

(FROM MESSRS. PEST CONTROL LTD.)

KENYA. *October*, 1948.

The first helicopter to fly in Africa took off from Khartoum on October 9th. It was a Westland Sikorsky operated by Messrs. Pest Control Ltd., and piloted by their Chief Pilot, Mr. J. E. HARPER, A.F.C. This was the outcome of much experimental work and an intensive spraying programme carried out in this country by the Company during the last year.

The first flight was a short test flight at an air temperature of 102° F. and the aircraft rose more sluggishly than in U.K., but it performed quite well during the next test flight the following morning at 07.45 hours, and lifted its full load at 92° F. This was then followed by a regular test flight every hour on October 12th to ascertain the lifting power and the performance in the hot, thin air of Khartoum. This capital of the Sudan is only 1,200 feet above sea level, but owing to the great heat the air density is equal to

Messrs. Pest Control's machine spraying in this country early this year.

4,500 feet over England. The machine had been fully tropicalised and fitted with special dust filters to protect the engine, and additional precautions such as special heat insulating covers had been made to protect the rotor blades against the great heat whilst standing in the sun. The sun temperatures in the Sudan are so high that after mid-day all metal parts can no longer be touched, and maintenance outside a hangar becomes impossible.

As soon as the air tests were completed the spraying trials with the helicopter gear, known as " Spray-copter Mark I," commenced on October 14th on the cotton plantations of the Sudan Plantations Syndicate, and flights at various heights using the same technique as in crop spraying in U.K. were carried out. The spraycopter gave a very good performance and counts carried out on the mortality of the cotton pests showed that the reduction of pests achieved was equal to that achieved by tractor driven power spraying machines.

Messrs. Pest Control have a fleet of 14 large ground spraying machines working in the Sudan where they had very much increased the cotton production through the control of a small insect called " Jassid," which causes the so-called hopper burn. This is by far the biggest campaign for the control of pests on agricultural crops in tropical Africa and incidentally, was the first chemical control operation of any agricultural pest in Africa and was pioneered at the instigation of the Sudan Government in 1945.

As soon as the trials with the aircraft flying very low over the crop started, the biggest danger to helicopter spraying in Sudan became evident. Birds feeding in the crop rose when the helicopter was overhead and were hit by the rotors. The first bird so hit was a swallow which was of course killed, slightly denting the leading edge of one of the rotor blades. As there are a great number of other birds, such as Ibises, flying out of the crop, the pilot had often to take evading action. The most dangerous, of course, are the big carniverous birds which soar up and make no attempt whatsoever to avoid the aircraft. When Mr. Harper was asked his impression after the first crop spraying flight he said, " The Spraycopter performance is good and I don't mind hitting the small birds very much, but I do dislike the five tonners !"—by which he meant the big vultures, of which there are a great number in the Gezira.

Another danger, particularly when landing or operating with very low forward speed, are the " Dust Devils." These circular winds travel very fast over the ground and are particularly dangerous on cotton plantations near the desert. Other difficulties are the big dust clouds raised by the slipstream of the landing helicopter which sometimes completely obscure the vision of the pilot.

After the entomologists of the Government Research Station and Messrs. Pest Control had satisfied themselves that the control of the cotton pests was adequate, a demonstration was staged for the Sudan Government on the 18th October near Messrs. Pest Control's headquarters at Turabi in the Blue Nile Province. The demonstration was attended by His Excellency The Governor General, The Deputy Director of Agriculture, The Financial Secretary, The Governor of the Blue Nile Province, and many other leaders of the country.

With the successful conclusion of this demonstration the Spraycopter commenced large scale spraying operations scheduled to last over a period of several months and which are still in hand.

Proceedings of an Extraordinary General Meeting

HELD AT

LONDONDERRY HOUSE, 19 PARK LANE, LONDON, W.1

ON DECEMBER 11TH, 1948 AT 2.30 P.M.

H. A. MARSH, A.F.C., A.F.R.Ae.S. *in the Chair*

The HON. SECRETARY read the notice convening the meeting which was then addressed by the CHAIRMAN.

Ladies and Gentlemen :

Having heard our Honorary Secretary read the notice convening this meeting and also having received a circular giving extracts of the proposed new rules and regulations and subscription rates, you will all know the reason for calling this Extraordinary General Meeting.

Taking the rules first, it has been obvious for some time that these require bringing up to date and in particular Membership qualifications have been very ambiguous and lax in certain respects. In point of fact the main difference between the present and proposed new rules, lies in such qualifications, and the alterations in other respects should call for very little comment.

From the Association's point of view, the proposal to raise the subscription rate is very important and unless this is agreed to, it is extremely doubtful if we can carry on and become self-supporting. Had it not been for the generosity of certain individuals and firms engaged in the helicopter industry, the Association could not have possibly paid its way to date, but we cannot expect to continue working on these lines. For your information I would point out that the expenses entailed in running the Association are kept to an absolute minimum. Our only paid employee is the Assistant Secretary, MISS MACPHEE, and all the remainder of the work is done in an entirely honorary capacity by the Honorary Secretary and various members of the Council and the Association.

The Journal, which I think you will agree is very well presented, is almost self-supporting on its advertisements, and it is hoped that by the end of 1949, it will be entirely so. This would not be the case unless the majority of the work was done by the Publications Committee, again in an honorary capacity.

The move to the new office, together with necessary equipment, was made possible by the generosity of a number of firms, most of whom have agreed to finance the project over a period of three years.

It is not a very difficult feat of mental arithmetic to assess the general financial status of the Association, when one considers that we have approximately 200 members at 2 guineas and 100 Associate and Graduate members at 1 guinea, making a total income of 500 guineas. Offset against this amount, the Assistant Secretary's salary, cost of lectures and meetings, auditor's fees, general office expenditure and other normal outgoings of an Association such as this, and the answer is fairly obvious.

If the proposed new subscription rates are agreed to, expenses kept within limits, and membership continues to increase at its present rate, it

is felt that the financial affairs of this Association can be considered as reasonably sound. I should point out that the Council have powers under the present rules and regulations to vary the subscription rates, entrance and transfer fees, but feel reluctant to do so without consulting the members.

You will notice that there are two proposals, each of which will be taken separately. Dealing with the first, the complete set of rules and regulations have been available for inspection at our Office for some time and it is not proposed, therefore, to have them read in detail here. Any particular point which you may wish to raise will be open to discussion and subsequent amendments if duly proposed, seconded and agreed to.

The new grade of Companion Member has been suggested in order that the Association may still retain the high level of prestige which it enjoys and yet be supported by those who have not the necessary technical qualifications. A certain re-grading will be necessary amongst those who are now Graduate members and this matter will be dealt with by the Sub-Committee of the Council.

Finally, before throwing the meeting open to discussion I would like to take this opportunity of thanking MR. CROCOMBE for his very hard work in revising the rules and regulations, and also MR. WINGFIELD, for his assistance from the legal aspect.

The meeting is now open for discussion on the first proposal.

The proposed alterations to the rules were considered in the ensuing general discussion. A letter containing several suggestions from MR. D. R. GARRAWAY was read to the meeting, and several members present had points to raise. Some of these were adopted by the meeting as amendments to the proposal.

The CHAIRMAN then proposed, and the VICE-CHAIRMAN seconded :—

That the draft Articles or Rules, a copy of which for identification has been signed by the Chairman, be adopted, with the amendments agreed by the meeting, as the Articles or Rules of the Association.

This motion was carried unanimously.

The CHAIRMAN, continuing, said, we will now deal with the second proposal. I have already explained in brief why it is necessary to suggest the new subscription rates, entrance and transfer fees, and do not consider this requires any further explanation from me. If you think it is necessary I will ask the Honorary Treasurer to read a short financial statement of the Association's affairs.

The meeting is now open for discussion on the second proposal.

In the general discussion which followed, more details were given concerning the cost of running the Association, printing and stationery costs, etc. These details are always available to members at the Associations' offices and are therefore not reproduced here. There were no objections to, or dissensions from the proposed new subscriptions.

The CHAIRMAN then proposed and the VICE-CHAIRMAN seconded :—

That the changes in members' subscription rates, and the introduction of entrance and transfer fees, be adopted.

This motion was carried unanimously.

There being no other business, the meeting closed at 3.55 p.m.

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OBJECTS OF THE ASSOCIATION

The objects of the Association are to collect, compile, and disseminate information of a technical and semi-technical nature pertaining to Helicopters, and all other types of Rotating Wing Aircraft.

The Association aims to work in close co-operation with existing Aeronautical Bodies on matters affecting its Objects, and it may act as an Advisory Body in the promotion of legislation calculated to be of benefit to the development of Rotating Wing Aircraft.

THE FULL DAY DISCUSSION ON HELICOPTERS

A Joint Meeting with The Royal Aeronautical Society was held on Saturday, 20th November, 1948, in the hall at the Institution of Civil Engineers, Great George Street, Westminster, London, S.W.1.

The Meeting was divided into three sessions : Morning, Afternoon and Evening. The Morning Session was presided over by DR. H. ROXBEE COX, D.I.C., F.R.Ae.S., F.I.Ae.S., President of The Royal Aeronautical Society, the Afternoon Session by H. A. MARSH, A.F.C., A.F.R.Ae.S., Chairman of the Helicopter Association. The Evening Session was devoted to General Discussion. The idea of holding the Meeting originated with The Royal Aeronautical Society, who extended an invitation to The Helicopter Association to participate. Normally the publication of the papers presented to such a joint meeting rests with the inviting body, but in this instance the Association also expressed a desire to publish the papers, which was readily agreed to Royal Aeronautical Society by the R.Ae.S. For this, and for the very considerable assistance which has been given to the Publications Committee by the Society's Editorial Staff, the Association is greatly indebted.

MORNING SESSION

General Problems of the Helicopter for Civil Use

DR. H. ROXBEE-COX, D.I.C., F.R.Ae.S., F.I.Ae.S.,
President of The Royal Aeronautical Society
in the Chair.

The CHAIRMAN opening the meeting, said he supposed that in aeronautics the helicopter was the dream which had taken longest to come true. He believed that LEONARDO DA VINCI had dreamed it and he was certain that JULES VERNE had done so. But there was a long period in a sort of borderland between dream and reality when helicopters were made which either did not fly or only just did so.

In the past few years the helicopter had truly become a reality ; there were many years of research and development ahead, but the helicopter had arrived. In the Royal Aeronautical Society the helicopter had for long been one of the matters to which close attention had been given and in the past a number of eminent people had presented papers on the subject as well as on its sister, the " Autogiro," before the Society and one or two eminent people had also given lectures against the helicopter and the " Autogiro." In recent years the helicopter had attained such importance, and its potential had been so widely recognised, that those who were enthusiastic for it had felt the need for the creation of a Helicopter Association ; in fact the Association had come into being in 1945 and had done a great deal of good work since. Many of its members, were also members of the Royal Aeronautical Society.

It was fitting, therefore, that the two bodies should meet together to discuss a matter of common interest, one which was the sole preoccupation of the Helicopter Association and one which the Royal Aeronautical Society

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believed to be of vital importance. Thus the joint meeting had been arranged, which they were glad to see was well attended. As President of the Royal Aeronautical Society, he was glad to acknowledge how much the Society welcomed the co-operation of the Helicopter Association in that joint effort.

He then introduced Wing Commander BRIE, and complimented him on the tremendous service he had rendered to the development of the helicopter and the "Autogiro." It was as long ago as 1935 that he had made history with an "Autogiro" off and on a ship at Spezia in Italy, and had repeated that sort of thing since. He did it in 1942 in Chesapeake Bay, and he had been an example and a stimulus to everyone engaged in that field, which was not always quite so popular as it had become today. He was with the Fairey Aviation Company just after the war, and since 1947 had been in charge of the Helicopter Unit of the British European Airways Corporation. He held Helicopter Aviation Certificate No. 1, was a Charter Member of the American Helicopter Society and a Founder Member of the Helicopter Association of Great Britain.

The Operational Point of View

By Wing Comdr. R. A. C. BRIE, A.F.R.Ae.S., A.F.I.Ae.S.

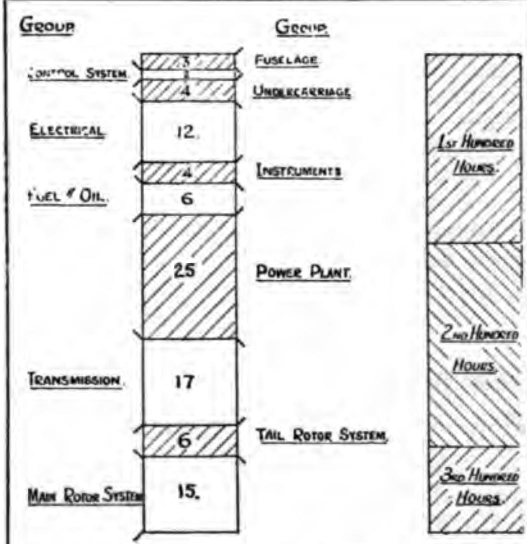
Although barely two years have elapsed since the helicopter was first certificated for civil use, the problem associated with its operation are sufficiently well defined to enable their nature to be discussed with reasonable facility. Actually, of course, there are twenty-six years, including many tens of thousands of flying hours behind this particular development, and it is quite logical therefore that the most advanced and successful type of helicopter to date embodies the basic and well proven rotor features of the Cierva Autogiro.

There is still much to learn, however, and at this stage of development it has in many ways been advantageous that, so far, the field of operational use has been a professional one. Difficulties have been minor rather than of a major category, but circumstances could easily have been otherwise had there not been constantly available the requisite background of skill and experience not only to cure, but what is of equal importance, to anticipate and prevent trouble before it could assume proportions of a serious nature. Additionally the limited number of helicopters in use has encouraged and made possible a rather intimate and desirable liaison between constructor and operator, which in turn has given the aircraft a reasonable opportunity to establish itself and prove its value under strictly controlled conditions of inspection and operation.

Essentially a product of the mechanical engineer, the helicopter with its clutch, gear boxes, driving shafts, universal joints, together with numerous ball, roller and needle bearings is a mechanism comparable in many ways to that associated with more normal and accepted means of surface transport. That with the aid of this transmission system the helicopter is capable of becoming airborne with an adequate degree of control is in itself remarkable. The fact that it also has performance characteristics which enable it to be

operated with facility from extremely confined areas, even under pronounced conditions of turbulence, provides adequate proof of the skill with which the pioneers have solved the major problems associated with the functioning of the rotor system.

To enable the subject to be viewed in a proper perspective it is opportune and appropriate to draw attention to current achievement in this country. Over a recent period of nine months covering more than 1,000 hours of experimental and day-to-day scheduled operation, there was on no occasion a cancellation or interruption of a flight due to the failure of a purely helicopter component.



Ratio of defects in various helicopter groups over 300 hrs. flying.

Incidence of overall deects over 300 hours flying.

FIG. 1.

Criticism, therefore, will be tempered with moderation, for it has been conclusively proved that no fundamental deficiency exists in a basic configuration. Whatever difficulties have arisen can be attributed to, and arise directly from a lack of refinement in detail design.

GENERAL PROBLEMS.

The general problems which I shall indicate and discuss fall under the headings of :—

Engineering, Flight Characteristics, and Operation.

The order indicated bears no particular significance, but the arrangement is convenient in that the effect of one has a direct association with, and influence on the others. Appropriate sub-headings might well be maintenance, pilotage and performance.

ENGINEERING.

The application of continuous power to the main rotor, the need for uninterrupted rotation of this component in the event of power failure, and the provision of adequate means for torque compensation, involves mechanical complexity and multiplicity of moving parts. Moreover, the natural vibrational characteristics of the rotor system are such as to make the aircraft as a whole particularly susceptible in terms of frequency and amplitude to quite small departures from allowable tolerances on linkages.

The working life of main rotor blade hinge bearings for instance is currently of too limited a nature. Compactness has been achieved at the expense of reliability, comfort and performance. Utilization is impaired, inspection schedules are prolonged, and costs of operation appreciably increased, not only through enforced servicing, but also by the interruption in the working life of other components which would best function if left alone.

Ideally all components should have a stated life, their ready replacement and precise interchangeability being of primary importance. Even so, the possible reduction in maintenance man hours thus affected is of itself inadequate unless the design layout of the aircraft has been such as to allow a concentrated effort to be applied, thus reducing turn-round time to a minimum.

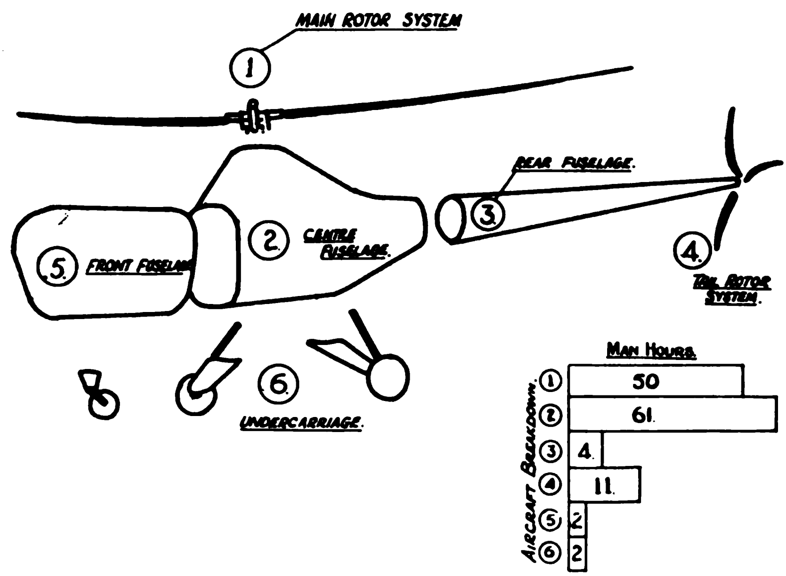


FIG. 2.

Accessibility for inspection and replacement of working parts also necessitates easily removable panels, jacking and sling points, hand grips and foot-rests. Dismantling and assembly of unitary components can only be accomplished with facility and little risk of damage by the provision of carefully designed tools and extractors.

The suppression of friction involves adequate lubrication, particularly with highly loaded bearing surfaces. If a grease gun has to be used, correct positioning of the connectors is a minor point with major implications, second only to the selection of the correct grade of lubricant.

Thus, sound engineering practice during the initial design period is a vital factor in the determination of maintenance procedures, and their relationship to and influence on utilisation. It is in fact the hard core of reliability, operability and earning ability.

FLIGHT CHARACTERISTICS.

Although the view is occasionally expressed that the helicopter is not difficult to fly, it would be an exaggeration to suggest that it is easy.

The efficiency of the control system as a whole is to a certain extent offset by delicacy required in the co-ordination of individual controls ; lack of uniformity in sensitiveness and feel, and the inability to trim for any sustained period. Present unstable characteristics are thus accentuated, and result in pilot mental and physical fatigue.

Whilst ballasting can be accepted as a pre-flight requirement to compensate for calculated C.G. displacement due to load carried, the lack of a satisfactory trimming device for use during flight necessitates the employment of the azimuth control, thus tending to restrict adequate control response to gusts, and adding to the difficulties associated with night and blind flying.

Careful investigation is required into the positioning of controls and their relationship to normal movements of the body : cockpit comfort in terms of seating, visibility and temperature ; and instrument display in terms of selection, grouping and readability.

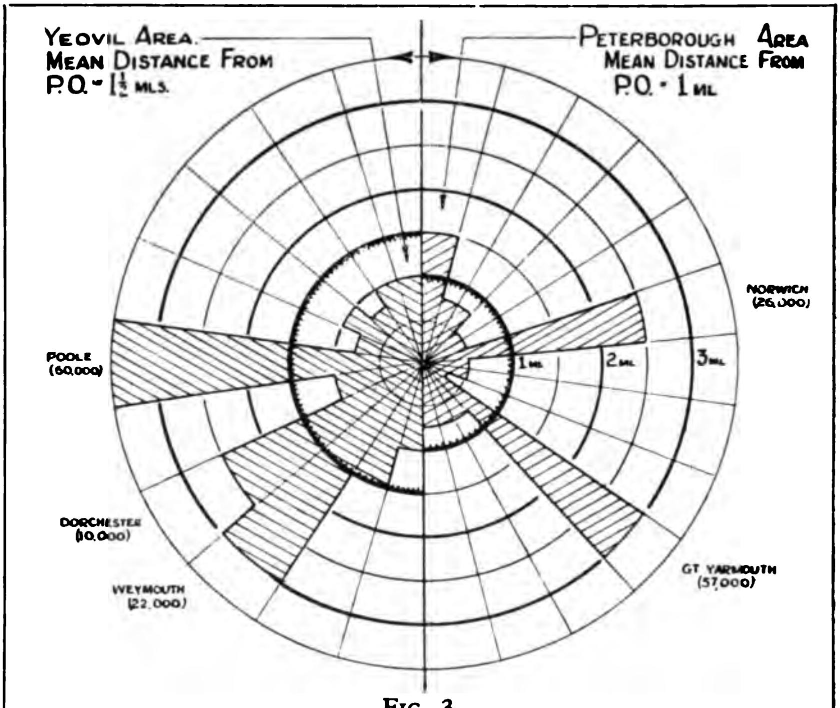


FIG. 3.

The psychological aspect of helicopter pilotage, and its co-related influence on instinctive reactions—especially during abnormal conditions of flight—needs to be explored, for the mental capacity to think may not always *be in step with* the physical necessity to act.

Operation from confined obstructed areas is appreciably influenced by performance characteristics. Maximum safety necessitates a rapid rate of climb at a steep angle of ascent during the take-off. Conversely, and to facilitate landing in the event of power failure, particularly with single engine types, the rate of descent must be slow at low translational speed. These latter requirements are functions of power and disc loading, respectively, the desirable values of which should not exceed 10 lbs. per h.p. and 2 lbs. per sq. ft. respectively.

OPERATION.

Two essential operational requirements are that the equipment used shall be reliable and safe.

Maximum utilization with minimum maintenance not only makes possible a high ratio of hours spent in the air to those spent on the ground, but this characteristic also breeds confidence amongst the operating crews in the reliability of the product they are handling.

Safety on the ground both to crews and nearby spectators must be assured by sufficient elevation of the blade tips of main and torque compensating rotors.

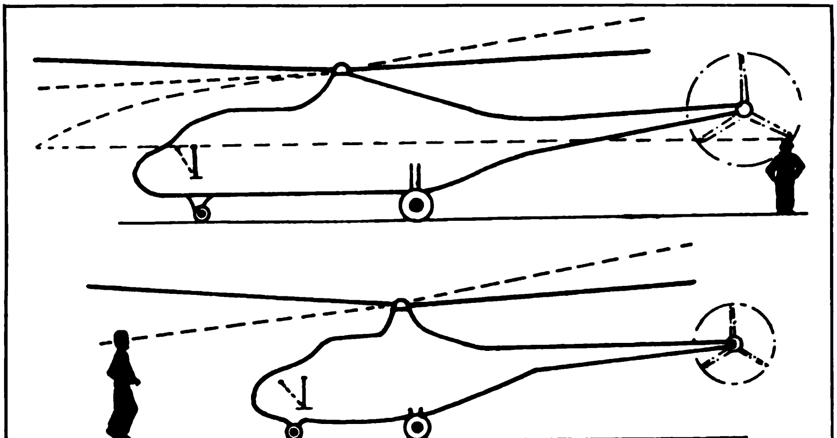


FIG. 4.

For safety in flight, visibility from the pilot's seat must not be impaired by the external effect of rain, or internal misting. Preservation of accepted standards of transparency is particularly desirable during night and blind flying operations at low altitude.

For the carriage of passengers the fuselage must be roomy and easy of access ; seating comfortable with good view externally ; vibrational and sound levels of a low order.

Route selection will to a large extent be governed by either the lack or limitation of normal surface facilities, three obvious examples being the centres of densely populated areas, mountainous terrain and water crossings. Hence to preclude the possibility of a forced landing due to power failure

under these operating conditions, a twin-engine installation is obligatory ; an essential performance requirement being the maintenance of altitude in the event of partial power failure.

Closely associated and parallel requirements to which brief reference should be made are the development of instrumental and navigational aids. Only by the ability to fly blind and at night will maximum utilization and operationally acceptable standards of efficiency and economy be attained. The accurate identification and use of small landing areas also involves the development of suitable ground lighting equipment, the precise nature of which has yet to be determined.

The economics of helicopter operation are at present such as to preclude consideration of other than highly specialised uses, a limitation which arises from high initial cost, and low pay-load capacity. Thus the field of application will be restricted until the one bears a closer relationship to the other.

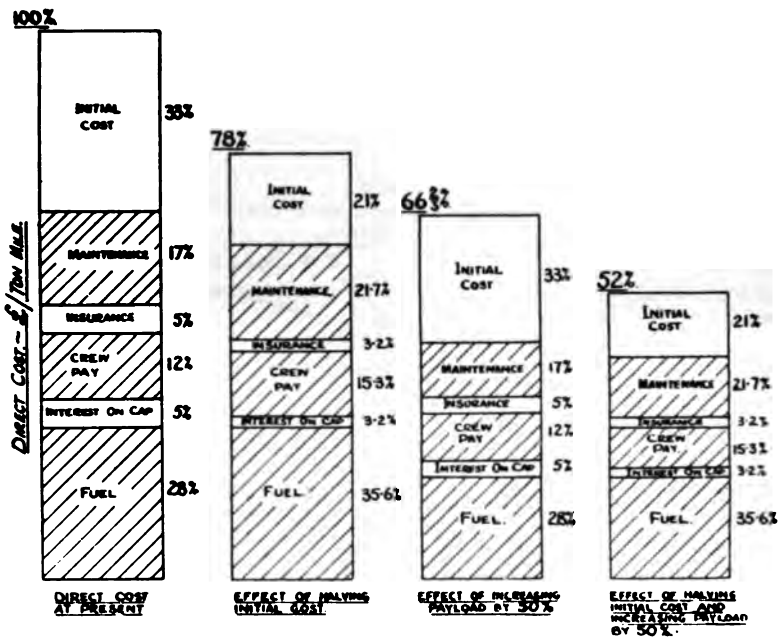


FIG. 5.

Whilst there may possibly be simple ways of appreciably increasing pay-load for freight or mail purposes, the solution as far as the human anatomy is concerned appears to lie in the development of bigger and better helicopters. Here the economic picture tends to assume a more pleasing appearance, for a preliminary study based on current practice indicates the possibility of effecting an appreciable reduction in costs per passenger mile and to a level more in line with accepted standards, with a 12–14 seater type of helicopter.

Conclusion.

In endeavouring to cover a fairly wide field in the short time available, the object has been to indicate that whilst the helicopter has already arrived in a practical form, its further development is closely associated with a solution being found to many relatively small but nevertheless important problems. The subject of economics is a wide one embracing many variables but there is little doubt that if there is to be any future in helicopter operation, if in fact the unique characteristics of this new means of transport with its independence of specially prepared landing grounds and its ability to save time are to be exploited to the full, then a fundamental requirement is that industry produces an acceptable product at an acceptable price.

To ensure overall reliability in service, the term engineering must be considered in its broadest sense during the conception of any commercial helicopter, so much so in fact that if necessary it would be well worthwhile to sacrifice performance, in terms of high speed, on the altar of utilization. Although man hours expended on maintenance have an important influence on engineering costs, hours of unserviceability reflect adversely on earning capacity.

In summing up, the stage of development already reached in the rotary-wing art indicates clearly the need for boldness and enterprise in making the best use of knowledge which already exists, rather than in scanning for fresh horizons with their inevitable uncertainties. There is nothing mysterious about what enables a helicopter to function, neither need there be any doubt about the direction in which its logical development should be pursued. If industry desires seriously and profitably to participate in this comparatively virgin field of vast potentialities, it must keep its head clear of the clouds of theoretical procrastination, and place its feet firmly on the ground of practical reality. This does not imply that improvement is not desirable, but it does imply the necessity for a sharp dividing line to be drawn between long-term research, and short-term development.

The latter is our immediate concern, and satisfactory solutions to the operational problems involved will only be reached expeditiously by mutual co-operation between those who produce and those who operate.

THE CHAIRMAN :

The Chairman said that, having heard a most interesting paper by Helicopter Pilot No. 1 and, hoping that they would hear later from Major Cordes the holder of the 2nd Certificate, the paper on technical problems was to be presented by the holder of the third ticket. Captain Liptrot had for a long time worked out the specifications and performances and things of that kind in the Air Ministry and the Ministry of Aircraft Production. At the moment he was thoroughly enjoying himself working with, and on and in, helicopters. At present he was Deputy Director, Research and Development (Helicopters) at the Ministry of Supply.

The Technical Point of View

By CAPTAIN R. N. LIPTROT, C.B.E., B.A. (Cantab.)

In a paper such as this, where I am asked to point a critical finger at the problems which we have to face in developing the helicopter for civil operation, it is inevitable that I should call attention to the shortcomings of the helicopters on which our experience rests so far. We have to remember that it is only a few short years since the helicopter reached the stage when it could be put in the hands of operators, and that the types on which the whole of our experience is based were born in the stress of the war years when they had to be put into use just as soon as they worked reasonably well. We have to admit that in many respects they are relatively crude in design, but, nonetheless, they have demonstrated that the helicopter is a practical transport vehicle and they have proved their worth in many fields. The helicopter has definitely arrived and will take its place in Civil Aviation as complementary to the fixed wing aeroplane for normal transport operations, and in a sphere entirely its own where its special characteristics make it capable of doing work which no other vehicle can perform.

When we critically examine the helicopter problem and the characteristics of available types, the special problems which stand out for investigation during the next stage of development are as follows.

VIBRATION.

The least informed on the subject will immediately realise that when the rotating lifting system of a helicopter is in translation, the velocities and, therefore, the lift on the blades on the advancing and retreating sides are very different, so that in the absence of some special arrangement there would be an upsetting couple about the longitudinal axis. This can only be corrected by a periodic change of the lift and drag forces on the blades, so we can expect to experience severe vibration.

The classic solution, of course, is the flapping blade introduced by DON JUAN DE LA CIERVA, which not only balances out the dissymmetry of lift, but relieves the blade roots of the periodic bending moments. This solution was elegant, but, unfortunately, instead of relieving the vibration problem, it actually accentuates it. This arises in several ways :

(*a*) The longitudinal flapping due to the forward motion results in a tilt of the tip path plane with respect to the axis of rotation and, in addition, the tip path plane has to be tilted by some form of periodic control in order to trim the aircraft at the attitude necessary for the speed. There is, therefore, a dissymmetry in the plane at right-angles to the axis of rotation and periodic forces in that plane.

(*b*) In addition, a flapping blade is subject to a Coriolis acceleration in the plane of rotation. Perhaps the simplest way of explaining this is to point out that, as a blade flaps upwards, the distance of the centre of mass from the axis of rotation decreases. For constant Kinetic Energy however, the product of this distance times the angular velocity must

remain constant, so that the blade in effect must accelerate as it flaps upwards and decelerate as it flaps downwards. This again involves periodic forces in the plane of rotation.

These two dissymmetries make it necessary to introduce a drag hinge, in order to relieve the blade root from the periodic bending moments which otherwise would tend to cause blade fatigue failure. The introduction of the drag hinge, however, leads us into further trouble, since the natural frequency of one of the modes of oscillation of the blade about the drag hinge is close to that of the periodic forces, so that we get an unstable hunting oscillation unless the freedom of movement of the blade about the drag hinge is restricted by damping or the natural frequency is raised by some means.

(*c*) As the ratio of forward speed to rotational speed increases, the retreating blade is more and more stalled, and for this reason again vibration is experienced.

(*d*) In the helicopter, where forward motion is obtained by tilting the tip path plane, there is an added axial flow through the disc, which reduces the effective angle of attack of the blades. The tip sections are affected less than the root sections, so that as the collective pitch is increased to maintain the average lift at the required value, the tip sections are overpitched and periodic stalling occurs.

Enough has been said to show that in forward flight we have a veritable witch's cauldron of fluctuating forces and a vibration problem which, though it may delight the heart of a vibration engineer, is one of the main headaches for the poor designer. Vibration indeed, rather than compressibility effects, may be the major factor in limiting the top speed of helicopters.

It is not within my province to indicate the lines of attack on this problem, that is for the aforementioned poor designer this afternoon, but I do want to introduce a word of warning. Some designers have considered that it is sufficient if the vibration is isolated from the aircraft, arguing that what the eye does not see—or rather what the body does not feel—the heart does not grieve about. This, of course, may be quite all right for the passenger who would not tolerate severe vibration, but it is simulating the ostrich in burying one's head in the sands of complacency. Even though isolated and, therefore, not impinging on one's senses, the periodic forces are still there and will promote fatigue failure. Personally, as one who persists in flying helicopters, I want to feel any vibration which may be present, so that should it increase in severity I know that something is wrong and can take steps to correct it.

Simplification of Control.

There is a widespread belief that the helicopter is difficult to fly, and we have all heard of pilots with thousands of hours on fixed wing aircraft who, in the early days of their conversion to the helicopter, have despaired, of ever getting the hang of the thing. It is perfectly true that existing helicopters prove to be extremely difficult to master in the case of some pilots. It is probably true to say that it is far easier to train an *ab initio* pupil, who has never been in the air before, than a very experienced fixed wing pilot. This in part is due to a psychological effect, in that the skilled pilot at first cannot bring himself to break all the rules of the game on which his very life depends on a conventional aircraft; for instance, in flying at

.maximum speed and deliberately coming to a standstill when some 20 ft. above the ground.

This aspect is well illustrated by a comment which was made during the first delivery flight of the Sikorsky XR–4 from Bridgeport to Wright Field. After landing at Rochester and doing some typical helicopter flying, one of the flying instructors on the field approached the pilot, saying " How do you expect us to teach these fledgelings to be good fliers? We spend months teaching them to keep flying speed at all times, and then you guys come along and make liars out of us with that cockeyed contraption. Doesn't the Army want pilots?" The remaining difficulty arises from the control characteristics of the helicopter.

In the fixed wing aircraft, although it has the six degrees of freedom of any body in space, we can get complete control from three angular controls and the throttle, since the aircraft can only move, at least continuously, in the direction in which its nose is pointed. The helicopter, however, as our American friends put it, can move in 362 directions, *i.e.*, along any azimuth as well as up and down along its axis. At least one additional control, therefore, is required—the collective pitch control. As the human being only has two hands and two feet, two of these controls, the throttle and the collective pitch have commonly been operated by one hand, and it has been the correct co-ordination of these two which has complicated the issue for the pilot. On top of this, in what has become the classic configuration, *i.e.*, the single main rotor with tail rotor for torque compensation, there is a further difficulty that any use of one control demands co-ordinated adjustment of other controls ; for instance, use of the tail rotor as a yawing control absorbs more power when turning against the torque reaction than with it, so that an appropriate throttle adjustment has to be made if height is to be maintained. Conversely, any adjustment to the throttle or collective pitch alters the torque reaction and so involves the use of yawing control. In sideways flight opposite rudder must be applied to keep the aircraft heading correctly, and this again involves throttle and/or pitch correction to maintain height.

Again there is a lag in response to azimuth control, though the control is extremely powerful and requires only very small application, and the response is normally far quicker in the rolling sense than in the pitching sense due to the big differences in inertia about the two axes. For this reason the pilot tends to overcorrect and to start violent swings which can result in an accident when flying close to the ground.

I have made something of a song about this difficulty of control because it is very real, but I would stress that it is only in the early stages that there is any real difficulty in control. Once the pilot gets the hang of the thing he can relax a little and flying becomes relatively simple. Nonetheless, flying helicopters demands a good deal of concentration, and in the next generation of helicopters the controls must be simplified and some of the co-ordination of the controls must be done for the pilot by some mechanical device in order to relieve the fatigue which today is quite severe.

Stability.

Mr. Stewart in his lecture gave a very full account of this problem, so that I need not go into detail. It will suffice if I say that, with the increasing use of the helicopter for commercial operation, we must be able to cater for

more and more adverse weather conditions. This is especially important for any of those uses where a rigid time schedule is demanded, as, for instance, for postal services. Intrinsically, the helicopter is the safest of all flying machines under low visibility conditions, since it can adjust its speed to be appropriate to the visibility at the time. Under blind conditions, however, where the pilot has to give his whole attention to navigation, radio, contacts with controls, etc., stability characteristics which might be acceptable under contact conditions even in low visibility become quite intolerable. Moreover, we can expect increasing use of the helicopter by private owners and others who cannot be given an aircraft with undesirable handling qualities, even though such poor qualities might be overlooked to some extent by skilled operators or for purely military use.

It is important, therefore, that the designers should give us improved stability, certainly under normal cruising conditions, and preferably under any conditions of flight, including hovering.

SAFETY.

The helicopter in common with the gyroplane is the safest of all aircraft, since it cannot be stalled in the ordinary sense of that term. Even though its speed is inadvertently reduced right down to zero, it will sink on a level keel under full control. In the event of power failure, it is converted to a gyroplane by pitch reduction and it can then make a safe forced landing into a small clear space exactly like the Autogiro. I realise that in making such a sweeping statement as this I am likely to be criticised, but I make the statement deliberately in order to stimulate discussion and get the answers from the designers.

There is, however, the difference in the helicopter that, in order to ensure the maintenance of r.p.m., the blade pitch must be reduced rapidly, otherwise, with the blade angles commonly necessary in ordinary flight, the rotor would slow up below the safety line in a few seconds. It is for this reason, coupled with the need to simplify the co-ordination of pitch and throttle, that some form of constant speed unit has been advocated, so that in the event of power unit failure the change to autorotation is immediate and automatic, and does not require any emergency action on the part of the pilot.

A word of warning is perhaps necessary on constant speed devices. Most of the devices proposed so far follow the lines of the constant speed propeller, *i.e.*, the governor operates direct on collective pitch. These devices are not satisfactory, since they introduce a hazard of their own in that, in the event of power unit failure very close to the ground, they take the wrong remedial action, since, under these conditions, the collective pitch should be increased, so using the kinetic energy of the rotor to arrest the landing, and as the pilot himself has no control over collective pitch he himself cannot take the right corrective action. On the other hand, if the governor operates on the throttle while co-ordination of pitch and throttle is done automatically for the pilot, the collective pitch lever becomes his master control and he still has to decrease pitch manually in the event of engine failure.

There is a further difficulty that, in the helicopter state, the airflow is downwards through the disc from above, whereas in the autorotative state it

is upwards through the disc. Also, if the engine failure occurs at slow air speeds, it is necessary to pick up speed in order to obtain the minimum rate of descent on the glide. To pick up the necessary air speed from hovering and to establish the new flow pattern, the average loss of height is of the order of 300 ft., decreasing with increase in air speed at the time of the engine failure. This is the one real potential hazard with the helicopter, and today pilots are instructed not to fly at low speed between, say, 30 ft. and 300 ft.

If the single-engined helicopter is to be permitted to operate over built-up areas, it will be essential to remove this potential danger and, in any event, it will have to be catered for, since so many of the practical uses to which the helicopter can be put—for instance, crop spraying—demand flight at low speed, even hovering, and at relatively low heights.

MAINTENANCE.

I think that nobody with operating experience on the available helicopters will disagree with me when I say that it is not the admittedly high initial cost of the helicopter today which has taken the gilt off what looked like a gingerbread to the early helicopter operators ; it is the maintenance costs due to the direct labour in short period inspection and overhaul, the excessive requirements of replacement parts, and the lost time due to unserviceability, which have damped the ardour of the most enthusiastic. It is true that maintenance crews with their built-up experience have made great advances in more rapid maintenance and servicing technique, but the costs have stabilised at too high a level.

Frequent dismantling and inspection to preserve airworthiness and smooth operation were well worthwhile when we were gaining experience, but that time has now been passed over, and in far too many existing designs when undertaking this work the maintenance crew is faced with an exceedingly complicated mechanism which is over expensive to take down and inspect, if only by reason of the sheer number of parts involved. For example, in transmitting the cyclic pitch control from a swashplate to the blades, too many parts are used. A very small amount of wear at each joint causes an overall amount of backlash in the system, which involves early scrapping of many parts. This motion could far better have been transmitted by a single link, increasing the life between overhauls and cutting down expensive replacements.

Ball or roller bearings at heavily loaded flapping, drag and feathering hinges are a source of continual trouble due to friction oxidation (the so-called " False Brinnelling ") which occurs in bearings where the angular movement is small. Friction oxidation causes very short bearing life as compared with a normal fatigue failure of the same bearing for single direction continuous motion, and it is only by reducing the load rating to about one-third of the unidirectional rotating rating that one can get a satisfactory life in the applications which we are now considering. This phenomenon, although known already in many industries, has not been realised generally by the helicopter designers, who have chosen their bearings on the makers normal ratings and, as a result, bearing replacement has been one of the major causes of high maintenance costs. Similar early failure of universal joints at points where angular change in direction of shafting is only one or two degrees

was a fruitful cause of unserviceability and need for replacements in the early operational helicopters. Research on this phenomenon and the development of bearings which will give longer life under oscillating motion at small amplitude is urgently needed for the helicopter.

Most helicopters are characterised by the complete inaccessibility of their power plants. Engines are enclosed in cooling air ducts, completely boxed in by fire-walls and close to fuel and oil tanks in such a way that they can hardly be seen even by the most conscientious mechanic, and so receive little or no preventative maintenance. Cases are known where the fuel tanks have to be removed to enable the plugs to be cleaned. The designer all too often in the past has been responsible for an arrangement in which the aircraft virtually has to be dismantled in order to change the engine. Maintenance under such conditions is naturally difficult and the designer must do better in the future.

Discussion.

W. Tye (Air Registration Board): On the general layout of rotor systems in present-day helicopters, Mr. HAFNER would probably say why it was best to react the main rotor torque with a little fan stuck several feet behind where any decent fuselage ordinarily stopped; Dr. BENNETT would then explain why the same function was so much better performed by a propeller asymmetrically mounted; and Mr. SHAPIRO might even try to convince the meeting that both these solutions were wrong, and that the real answer was to suspend the helicopter from three remote corners. Perhaps the problem was comparable with one debated many years ago on monoplanes, biplanes or triplanes, and whether the tail should be in front or behind. He did not know who was right or who was wrong about the helicopter, but insofar as any residual engineering instincts were left to him, these instincts rebelled against all these configurations. His instincts did not tell him what a helicopter should look like, but he hoped that someone might supply the answer. He admitted that these criticisms might be quite unjustified.

They were at the beginning of the development of the helicopter into a sound commercial vehicle, but if helicopters were to be made commercial vehicles, they must be more efficient (in the broadest sense), and safety, which had so far been good, must keep pace with the increasing uses of the helicopter.

The authors had referred already to a number of directions in which improvements could be achieved, both in efficiency and safety. These two developments must proceed hand in hand, although, inevitably they would pull in opposite directions. The aim of airworthiness people was to see that a reasonable balance was maintained between the two.

The problem was by no means new, for it had to be faced every day with fixed wing aircraft, but in that latter sphere they had many years of experience to guide them. In the helicopter field the experience was much shorter, and he felt it would be easy to allow safety to suffer in the interests of efficiency, or vice versa. The only satisfactory answer was to obtain as much information and as quickly as possible about the way in which helicopters behaved in operations or simulated operations.

The following were examples of things they needed to know:—

The loads applied by the pilots in manoeuvres; Information to assist in the determination of fatigue conditions for rotor blade design; The velocities of descent in normal and emergency landings; The use of engine power in typical flights; The effect, if any, of ice on the rotor blade; The degree of stability necessary for safety.

That list was not intended to be exhaustive.

He had served on the Air Registration Board's Rotorcraft Requirements Co-ordination Committee, on which designers, engine constructors, operators, and specialists from the R.A.E. and the Ministry of Supply were striving to prepare a design code which would establish and maintain a reasonable level of safety. The Committee's task was made extremely difficult by the absence of the kind of information to which he had referred.

O. Fitzwilliams (Westland Aircraft Ltd.) *Founder Member*: He wondered if Mr. TYE objected to sailboats. He could think of nothing more asymmetrical than those time-honoured vehicles. From a performance standpoint it did not seem to matter in practice how many rotors there were or where they were placed, the result was always a lemon ! It was a matter of engineering convenience ; they could not do what was required with just one rotor without some form of jet drive, and they had to choose the most economical means.

The authors of the first two papers, and to a lesser extent the authors of the later papers (from the summaries he had read) had shown a tendency to continue at this meeting the habit of grumbling together about their mutual shortcomings. That was a valuable and salutary purpose of the Helicopter Association, but he doubted whether it was proper at a meeting such as that with the Royal Aeronautical Society. Surely one object of the meeting was to enable the helicopter fraternity not only to explain their problems but also the reasons for their obvious enthusiasm, in the hope that more of the highly qualified and experienced people in the aviation industry might be led to see in the helicopter a fascinating and thoroughly useful outlet for their talents. He could not help feeling that those with a wider experience of aircraft engineering along orthodox lines would have noticed that most of the complaints which had been made that morning about the helicopter were of a curiously minor nature. The main hold-up in helicopter development was not because of the existence of mysterious problems which could be handled only by a genius ; the main holdup was, and always had been, lack of funds and lack of volunteers from the ranks of the more talented and experienced aircraft engineers.

The position was by no means so pessimistic as might be assumed from the papers. He thought that, far from being complicated, every successful rotor system now flying was of a simplicity approaching crudity and the contrary impression was an illusion arising from unfamiliarity with the simple swashplate mechanism involved. The reliability of the mechanism was astonishing, considering the small extent of the facilities which had been available. Improvement was a matter of skilled, but nevertheless straightforward, aircraft engineering. Surprising attention had been paid to the servicing aspect in the existing helicopters. It was not true to suggest that they were lacking in proper provision for maintenance. Also, their power plants were reasonably accessible. They were not perfect, and to suggest that maintenance was entirely satisfactory would be untrue, but in at least one type that was operating there had already been serious complaints that the time and energy called for on inspection schedules was out of all proportion to the trouble that was actually found in the machine when it was inspected. Some of the major parts, the tail gearbox and so forth, were not even dismantled for inspection over a period of something like 600 hours. That was the present generation of helicopter.

Insofar as difficulties of this sort did exist, they did not involve anything peculiar to the helicopter nor anything which could not be cured by straightforward application of money and man-power in the design offices. Without these progress must remain slow.

The same remarks in the same degree could be made about stability and most of the other problems discussed. In considering stability, they must think of the use to which helicopters were put and the kind of helicopter with which they were dealing. For passenger operations twin-engined helicopters were needed because passenger operation meant efficient service into and out of the principal towns.

At present helicopters are mostly single-engined and mainly for specialised duties, such as crop spraying, rescue and so forth.

In a recent lecture to the Helicopter Association Dr. SISSINGH had described a most elementary collection of bars and links which could perform all the functions of an otherwise highly expensive automatic pilot. He did not think there was a designer in this country who would at the moment bother to incorporate it, for it was just not worth while in present conditions. Later on, when they needed stability in passenger operations, and a great deal of work had already been done on the stability of the multi-rotor arrangements, when the law of supply and demand called for it, stability would be provided.

Much the same could be said of cures for vibration. He believed Mr. SHAPIRO would point out that the vibration which bothered the occupant of the helicopter at the moment was due mainly to lack of foresight and effort in the design offices, which was unavoidable at the moment. The vibration which was really inherent in the helicopter and which could not be eliminated, was small compared with the vibration of ordinary

surface means of transport. If they wanted to fly helicopters at speeds much above 140 m.p.h., where vibration problems really became severe, they might have to use forward propulsive airscrews and possibly fixed wings, but such aircraft should probably be called " convertaplanes," rather than helicopters.

The further development of helicopters was dependent mainly on the money and manpower available, but the helicopter manufacturers were not waiting ; they were going ahead with the production of helicopters, confident that customers would buy and use them and thus provide the funds necessary to bring the helicopter to the state of perfection desired by the operators.

L. S. Wigdortchik (B.E.A. Helicopter Unit) *Founder Member* : He believed the future of the helicopter was dependent on its commercial potential to an extent that set it right apart from the fixed wing aircraft. The latter, because of its over-riding military value, had never lacked funds for its development, but such an all-important incentive did not exist for the helicopter. Therefore, they must understand from the outset that it was essential to make the helicopter a commercial proposition with a realism, and even ruthlessness, not hitherto seen in aviation.

There was no longer any real problem in making a helicopter with acceptable flying characteristics ; and, as the authors had shown, the practical problems were well on the way to solution. The real problem was to produce a helicopter that could be made a commercial success by an efficient operator.

Close economic analysis of contemporary helicopters showed that the operating costs were high and out of all proportion to the general service rendered, mainly because of the high ratio of initial cost to disposable ton-miles per hour. Commercially they could only be considered in roles where either the payload against distance carried had a high intrinsic value, or a special service or novelty aspect was exploited.

To some extent it might be possible to produce cheaper and more efficient machines by simplification of detail and overall design, without impairing ultimate performance and reliability. Was it really necessary to follow fixed wing requirements for undercarriages, structures and other design criteria ? Similarly, could requirements for vertical flight performance be relaxed, in order to be able to operate at heavier all-up weights ? The engine-off landing was no longer such a hazard as they had thought ; thus, his suggestion might be seriously considered. Again, many existing helicopters carried excess structural weight, because of the unknowns that existed during their design stage. To-morrow's helicopters would benefit by later experience.

He believed that a great advance in commercial characteristics would be obtained with the large helicopter, in the 1,500-3,000 h.p. class, since all indications showed that such machines would have a much lower ratio of initial cost to disposable ton-miles per hour. Such an aircraft would have to be able to maintain a ground speed of 100 m.p.h. against a headwind of 40 m.p.h. over blocks of 250 miles and must be able to carry 20-30 passengers.

It was no use having helicopters if they did not know how they were going to use them and over what routes. The work being done to-day was valuable in the operating lessons that were being learned, and from that they must take their guide. His own view had always been that the helicopter was best suited for passenger transport because of its ability to reach city centres, but it must be able to offer a service that soon became indispensable and that could only be done by a service with a utility far in excess of anything that went before.

The history of vehicles showed that they became really economic only when mankind evolved his society around their potential. The helicopter had a chance to become part of the human fabric to an extent which might confound their thoughts to-day.

Air Commodore W. H. Primrose, *Member* : In his British Commonwealth and Empire Lecture* Mr. MASEFIELD had laid down four basic requirements for air transport to achieve its role as an economic medium in the communications system :—

1. Efficient aircraft.
2. Efficient operators.
3. An efficient ground organisation (meaning adequate airports and adequate air traffic control).
4. An air faring outlook—by the public.

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* MASEFIELD, P. G. Fourth British Commonwealth and Empire Lecture. Some Economic Factors in Civil Aviation. JOURNAL R.Ae.S. Oct. 1948.

The first and second of those requirements had been dealt with adequately in the first two papers and more would be heard, he hoped, from the other papers. But there was a complete absence of any mention of the Masefield requirements 3 and 4.

Let them assume that within the next five years intensive research and development would result in the production of the acceptable product at the acceptable price demanded by the operator, together with the evolution of a satisfactory operational technique and trained personnel. How far advanced would they be towards the practical economic utilisation of the helicopter as a means of speeding up communications if there were no developments in the provision of city centre landing sites and other ground facilities? Without those, few of the advantages which the special characteristics of the helicopter possessed over other forms of transport could be reaped. It would be like having efficient trains or buses without railway tracks, roads, stations or termini. Would they not be back at the situation that faced them in the late 1920's, with the then Prince of Wales making his appeals to Lord Mayors and Corporations to provide airports for their cities to enable them to operate internal air services?

The fourth requirement and the one which PETER MASEFIELD had considered most important, was an air faring outlook. Even the provision of "City Copter Courts," as they had been called, would not ensure the full economic utilisation of the helicopter transport potential, unless the public were educated to be helicopter-minded. Again, they should learn from the lessons of the past and remember ALAN COBHAM stumping the country in his efforts to make the public air minded and air travel conscious.

Another matter that he would like to hear discussed was that of the type of undercart or alighting gear for the helicopter of the future. Were they not in danger of following too slavishly the type of undercarriage that had been developed for the aeroplane, in the same way as they copied the lines of the horse-drawn carriage in the first motor cars?

The aeroplane, because it had to run along the ground before it could become airborne, and on landing after it ceased to be airborne, *must* have some form of wheeled undercarriage. The helicopter, because of its ability to take off and land vertically without forward run, did not require the wheeled undercarriage. There seemed to be considerable room for the development of an alighting gear which would save a lot of weight and/or drag and at the same time would provide a good shock-absorbing medium. Such a landing gear could also be made to spread the load over a larger area and so make less stringent the bearing strength requirements of landing sites. If it were an air pressure type it might also provide the facility for the helicopter to alight on water and float in a stable condition. The advantages of such an amphibious type required no stressing.

A point in the economics of helicopter operation that was too often not fully appreciated, or was entirely overlooked, was that of its facility for rapid turn-round. That might well give it the advantage of at least 10 minutes at each end of a stage journey over the normal transport aeroplane. On a stage journey of 100 miles at 100 m.p.h. enough time would be saved for an extra journey every three hours or so, which would go a long way towards nullifying the higher translational speed of the aeroplane, apart from time saved in surface travel between city centre and airport. He thought that Mr. MASEFIELD had not made full allowance for that factor in his comparison of the aeroplane and the helicopter on the short stages.

S. Scott Hall (P.D.T.D. (A) Ministry of Supply): He appreciated that Mr. FITZWILLIAM had promised that when they had helicopters with multi-rotors the problem of stability would be solved. But it was important to consider the helicopter as it was to-day, and he understood that it still lacked stability. He had tried to fly an early helicopter and it had seemed to him very much like trying to balance a ball on the end of a pin; it was certainly unstable.

There was also the difficulty of flying blind, and he hoped that these two points would be dealt with adequately in the discussion because he regarded them as being fundamental. Good stability and blind flying qualities were absolutely essential to operation in bad weather.

The authors of the papers had presented with clarity a subject which to many of those present was very obscure.

A. McClements (B.E.A. Helicopter Unit) *Founder Member*: The helicopter needed development before it assumed its full effectiveness as a vehicle of transport;

but if they came down to fundamentals, economics would probably play a much bigger part than anything else in determining when helicopters would become available as a means of transport to the "man in the street." One of the factors affecting economics was closely related to helicopter engineering and maintenance procedures, and much could be done by the designer and operator which would reflect favourably on the overall economic picture.

Maintenance methods at present slavishly followed the tradition of past aeronautical practice. They inspected machines at given periods, pulled them to pieces at other periods and put them together again, often doing more harm than good in the process. More important they kept the machines on the ground during those performances. Some idea of the drain which such methods imposed on the operator could be gathered from his own experience, which showed that for every hour flown by a helicopter they kept it standing on the ground tinkering with it for approximately 2½ hours. That figure bore no relation whatsoever to the reliability of the type of machine in question. In actual fact, current certificated helicopters were known to be remarkably trouble-free.

Why, then, was the work done? The main reason was because they did not know enough about the product they were handling and were forced to find out the hard way. Such methods gave some assurance against breakdown and accident, but they were so unattractive economically as to make it obvious that attention must be paid in future designs to ensure higher utilisation and less maintenance effort. They would go a long way towards their goal, and at the same time probably make one of the most forward steps in helicopter development for some time to come, if they worked on the following lines :

(*a*) A realistic balance must be struck between performance and possible useability. The designer must try to give the operator the maximum possible utilisation potential for the minimum amount of engineering maintenance effort. The future commercial helicopter which would be popular would not necessarily be the one which had the highest performance, it was more likely to be the one which was reliable and required little attention.

(*b*) The present system of maintenance in which all effort was aimed at discovering defects by searching for them at frequent intervals should be abandoned. The manufacturer should find out what the lives of his helicopter components were, and let the operator leave those components alone until their lives were over and then change them. This implied considerable effort by the manufacturer in the initial stages of a project, embracing bench and laboratory testing and full-scale evaluation under conditions of controlled intensive flying. Such effort should be undertaken before the machine was offered for regular operation.

(*c*) The closest attention should be paid to interchangeability and accessibility so that parts could be replaced quickly and without the need for "fitting."

(*d*) The closest attention should be paid to easing the problems of servicing.

(*e*) Adequate special tools should be provided so that servicing and maintenance could be done easily and quickly.

There was nothing particularly original about those suggestions. The lecturers had clearly touched on most of them and people interested in fixed-wing aeroplanes had been making similar suggestions for some time. There was one important difference between the commercial aeroplane and the commercial helicopter ; the helicopter had no background of convention to overcome and they had a golden opportunity to start it off properly.

There was no point in just saying that the helicopter would have a great future, because its future would depend solely on what they made it. Being new, they had an ideal opportunity of exploiting to the full the enormous possibilities which it undoubtedly had. They could only do that by adopting the methods best suited to it and not necessarily those related to any existing form of transport. The selection of such methods would call for the closest co-operation between designers and operators.

Group Captain E. Fennessy (Decca Navigator Co. Ltd.) : The navigation of the helicopter was a very different problem indeed from that arising with the fixed wing aircraft. Bearing in mind the vast size of modern airfields used by fixed wing aircraft, it was not so much a problem of finding those airfields ; indeed, they could hardly be missed. The major problem of fixed wing aircraft was to get them down in safety. On the other hand, the helicopter had to land in a small space, which probably had to be approached be a devious route. The problem was more akin to that of marine navigation, where ships had to proceed by devious channels in close proximity

to dangers in order to reach restricted and confined ports. There was one most important difference between the problem of navigating a ship and that of helicopter navigation. In a ship, it was possible to carry considerable amounts of navigational equipment, without regard to weight, and extensive facilities could be provided for plotting the ship's position and course on Charts. In the helicopter, navigational aids must be of minimum weight, and furthermore, since the pilot was fully occupied with the problem of flying the helicopter, no technique involving any procedure of plotting the position would be acceptable.

The pilot must have provided for him, in an automatic fashion, adequate information to enable him to follow the proper route in any weather and without his being involved in any manual operation, other than that required to switch the equipment on at the start of the flight.

It was encouraging to note that many of those concerned with helicopter operation appeared to be well aware of these operational requirements. As a radio engineer concerned with co-operating with the aeronautical engineers and the operating authorities, it was a pleasant experience to find such an awareness of the necessity for an early solution of these problems. There was, indeed, a more live realisation of the need to solve the problem then was perhaps existing in the field of fixed-wing aircraft navigation and control.

The Decca Navigator Company were working in close collaboration with the Helicopter Development Unit and the Research and Development Division of British European Airways, on the solution of these problems of automatic navigation. The principles being followed were that firstly, a radio navigation system should be provided which gave the adequate basic information and the aircraft's position, and it had been found in trials conducted by British European Airways that the Decca System provided this basic facility. To interpret this information to the pilot in an automatic manner, the Track Control Unit had been developed. This was an electronic interpreter, in which the aircraft's position derived from the Decca System, was converted to a simple meter display, telling the pilot his position with respect to track, in terms of both his distance to left or right of track, and his distance to fly along track to destination. The pilot had therefore only two meters to consider, one told him when he was on track, or how far he had deviated to left or right ; the other told him how far he had to fly to reach his destination. An equipment meeting this requirement had already been flight tested, and further models were under construction.

It was not unwise to predict that within a year or two, it would be possible to present the pilot with an automatic map display of his position.

The far-sightedness being shown by British European Airways in both the technique of helicopter flying and of automatic control would undoubtedly result in bringing much nearer the day when the helicopter would be widely applied to many forms of communication. The mistake was not being made of producing a good flying machine and then finding that they were not able to operate because of lack of necessary blind flying and navigational facilities.

AFTERNOON SESSION

The Constructor's Approach to the Problem

H. A. MARSH, A.F.C., A.F.R.Ae.S.

Chairman of The Helicopter Association

In the Chair

LADIES AND GENTLEMEN,

Before calling on the first lecturer this afternoon, I would like to take this opportunity, on behalf of the Helicopter Association, of thanking the President and Council of the Royal Aeronautical Society for their courtesy in inviting us to share to-day's proceedings. The idea of a full day's discussion on helicopters originated with the R.Ae.S., but it can hardly be a coincidence that all those invited to read papers are members—I should say Founder Members—of the Helicopter Association, three of them being Council Members and one an ex-Council Member. You are no doubt all aware that the Helicopter Association is of comparatively recent formation and owes a big debt of gratitude to the Royal Aeronautical Society, and other bodies for all the help and guidance they have given in the three years since the Association was incorporated.

This morning you heard papers read giving the operators and technicians point of view on helicopters and this afternoon you will hear three papers giving the constructors' approach to the problems.

As our time this afternoon is limited I am going to ask the Lecturers to present their papers in turn with no pause for discussion between the papers. We will then conclude the afternoon proceedings by having a short discussion on all the papers ; this discussion can continue after the Tea Interval.

The first paper will be presented by DR. J. A. J. BENNETT who will describe some special aspects of the Fairey Gyrodyne—the helicopter which now holds the world's speed record.

DR. BENNETT was educated at Glasgow, London and Gottingen Universities and has specialised during the past 18 years on rotary wing development. He worked very closely with the late SENOR DE LA CIERVA and his present appointment is that of Head of the Helicopter Division of the Fairey Aviation Company. He was largely responsible for the Aerodynamics of the early Weir's single seater autogiros, the direct take-off Cierva Autogiro and is solely responsible for the Fairey Gyrodyne. I now ask Dr. Bennett to read his paper.

The Fairey Gyrodyne *By*

J. A. J. BENNETT, D.Sc., Ph.D., F.R.Ae.S.

THE GYRODYNE APPROACH.

The success of the helicopter today is primarily the result of a background of rotary-wing experience covering many years of research into the problems of the gyroplane. This simple form of rotorcraft, proposed by JUAN DE LA CIERVA, was developed to a stage at which vertical take-off and landing were normal maneouvres and were no longer exclusive features of the helicopter. Only the ability to hover remained as the unique advantage of the power-operated rotor—an advantage for which a heavy penalty had to be paid. The general problems of the helicopter for civil use are concerned mainly with an alleviation of the penalty that hovering has incurred.

The hovering requirement had led to the use of twin contra-rotating rotors in spite of their greater complexity, to heavy disc loadings with their poor gliding performance, to rotors of high pitch which require rapid action on the part of the pilot to prevent them from stalling in the event of power failure, to complicated devices for governing rotor pitch or engine speed arising from the need for control simplification, to an excessive forward inclination of the aircraft in forward flight, and to periodic blade-tip stalling which had imposed a new limitation on top speed. In other words, the ability to hover could be bought at the expense of simplicity of control, safety, compactness of design, and comfort.

In the design of the Gyrodyne an attempt has been made to regain some of the ground that was lost. The propulsive powered-rotor and the autorotative rotor represent two extreme forms of rotary-wing aircraft, and the relatively non-propulsive rotor of the Gyrodyne avoids certain limitations of the two extremes. The possibilities of the Gyrodyne principle were discussed as long ago as 1940 (Ref. 1) and a description of the present machine was given in a recent lecture to the Helicopter Association (Ref. 2). It is proposed this afternoon, therefore, to mention only those particular features of the Gyrodyne which have a bearing on the problems discussed at the Morning Session.

COMPACTNESS OF DESIGN.

In several respects the Gyrodyne configuration was the forerunner of the form of helicopter developed to a practical stage by IGOR SIKORSKY. Both utilise a single lifting rotor in torque balance with a single non-lifting airscrew, both have branch transmission systems of variable power distribution, and both obtain direct control in yaw from foot pedals, which vary the collective pitch of the non-lifting airscrew. The manner of operation of the two is therefore much the same, the main difference being one of degree only, in regard to control response. The Gyrodyne, due to its compactness of design, would be the more manoeuvrable but for the stabilising surfaces at the tail.

Where the two differ in principle is in the azimuth location of the non-lifting airscrew and in its distance from the rotor axis. Taking into account the many uses for helicopters, it is thought that forward flight will occupy about 95% of the total life of the aircraft. An even higher percentage might apply to helicopters used only for transport. Consequently, if the non-lifting airscrew is located laterally, as in the Gyrodyne, the power required for torque balance is utilised for the useful purpose of forward propulsion throughout practically the whole of the normal operating life.

On the other hand, with the non-lifting airscrew located at the tail, the power applied to it is a total loss under all normal operating conditions. To keep this loss at a minimum, the tail location requires a sacrifice of compactness, and this in general results in extra structural weight. There is no such requirement for the Gyrodyne.

Low Rotor Power.

The inevitable decrease in power loading of the propeller in forward flight decreases the proportion of power delivered to the rotor as the forward speed increases. As a result, the main transmission of the Gyrodyne need be fully loaded only during the take-off and landing, thereby ensuring a high margin of safety at cruising speed, the normal condition of flight of a transport helicopter.

There are, of course, many uses for the helicopter where forward speed is unimportant and where the main requirement is to lift the maximum load that the available power will allow. For such duties, the non-lifting airscrew of the Gyrodyne might be moved farther outboard, but this need not be overdone at the sacrifice of compactness, because the Gyrodyne rotor can have a low disc loading and thereby lift the same load for less power than a rotor of high disc loading.

The relationship between the power (x) in the branch transmission of the non-lifting airscrew, per unit total power in both transmissions, and the distance (a) of the non-lifting airscrew from the rotor axis, expressed as a fraction of the radius of the rotor, is simply $x\,(1 + 6a) = 1$, assuming a tip speed of 660 ft./sec. and a power loading of 5 for the non-lifting airscrew. If a is about one-third, as in the Gyrodyne, x is also about one-third, or, in other words, two-thirds of the nett power available, after allowing for engine cooling and transmission losses, is applied to the rotor.

In spite of the saving in structural weight due to compactness of design and to the lower power requirement for the main transmission, and in spite of the low disc loading and better weight-lifting performance of the Gyrodyne rotor, it may be thought that too much power is applied to the propeller in vertical flight. This power, however, can be considered as a reserve, and vertical climb can be boosted temporarily whenever necessary by the relatively simple expedient of performing axial turns.

Except at air displays, a helicopter need hardly ever climb vertically out of the " ground cushion." It is a much safer procedure to climb at the forward speed requiring minimum power and a steep angle of ascent at this speed is of greater importance in practice than a high rate of vertical climb. For take-off at altitude, a strong " ground cushion " is an advantage and this is assured by the low disc loading of the Gyrodyne.

Low Disc Loading.

Unrestricted by rotor blade clearance problems, the Gyrodyne has a lower disc loading than is possible with most other forms of helicopter. This gives the Gyrodyne certain advantages in both power-on and power-off flight. As the extreme limit of power loading of a rotor is equal to the reciprocal of the induced velocity, and the induced loss at take-off is roughly twice the profile loss, the limiting power loading of the helicopter is almost inversely proportional to the square root of the disc loading. Thus, if the disc loading of the Gyrodyne is 20% less than that of other helicopters of

equal gross weight, the Gyrodyne rotor can lift the same load for 10% less power. This factor is mainly responsible for the low rotor power required in the Gyrodyne, the load sustained per rotor h.p. probably exceeding that of any other helicopter.

A similar advantage is obtained in power-off flight. The low disc loading minimises the sinking speed in a glide and ensures the safety of the occupants in an emergency landing. Even at night, or in a forced landing due to fog, a helicopter of low disc loading could descend and land almost vertically without disastrous results. The use of pitch change for utilising the kinetic energy of the rotor for momentary hovering prior to a power-off landing should be considered as an additional safety measure in helicopters, rather than a necessary manoeuvre upon the precision of which alone the safety of the aircraft depends.

There is a general impression that a low disc loading, like a low wing loading for aeroplanes, is detrimental to efficiency at cruising speed. This is not necessarily so because it is not disc loading, but blade loading, that governs the profile power loss. The blade loading, being the ratio of the disc loading to the solidity, can be kept relatively high by choosing a low solidity. In the Gyrodyne, the solidity is only 1% per blade and the blade loading is 75. The high blade loading ensures a low profile power loss at top speed, and the low disc loading a low induced power loss when hovering.

Low Pitch.

There is no doubt that low disc loading and low rotor pitch contributed to the remarkable record of safety achieved by rotary-wing aircraft in the pre-helicopter era. In contrast to most other helicopters, a result of the low-pitch operation of the Gyrodyne is that it can not be stalled under any condition of flight by a possible misuse of the controls.

Apart from safety, low pitch has other advantages, not the least of which is its effectiveness in minimising vibration—the " bugaboo " of rotary-wing aircraft. Helicopters which are rough in operation at high pitch in forward flight are usually quite smooth at the same forward speed in autorotative flight.

The necessary rotor power for sustentation is absorbed in the Gyrodyne by its relatively high tip speed and, because the tip-path plane is never tilted excessively forward for propulsion, the rotor remains at low pitch over the whole speed range.

Independent Propulsion.

A significant feature of the Gyrodyne is its independent means of propulsion. It enables both the fuselage and the tip path plane to remain substantially level under cruising conditions. This attitude is not only the optimum one in regard to drag and passenger comfort, but removes what had become an important barrier to the propulsion of helicopters. Periodic lift distribution in autorotative rotors had resulted in stalling of a part of the retreating blade near the root, but, in the helicopter with a forwardly-inclined rotor, periodic stalling can occur at the blade tip. This is due to the relative air speed having a down-flow component. Operation of the helicopter close to the periodic stall of the retreating blade is limited by vibration. No matter how much power is available, therefore, it cannot be utilised for propulsion beyond the periodic tip-stall barrier.

The international speed record for helicopters, now held by the Gyrodyne, can undoubtedly be exceeded in future by helicopters with propulsive

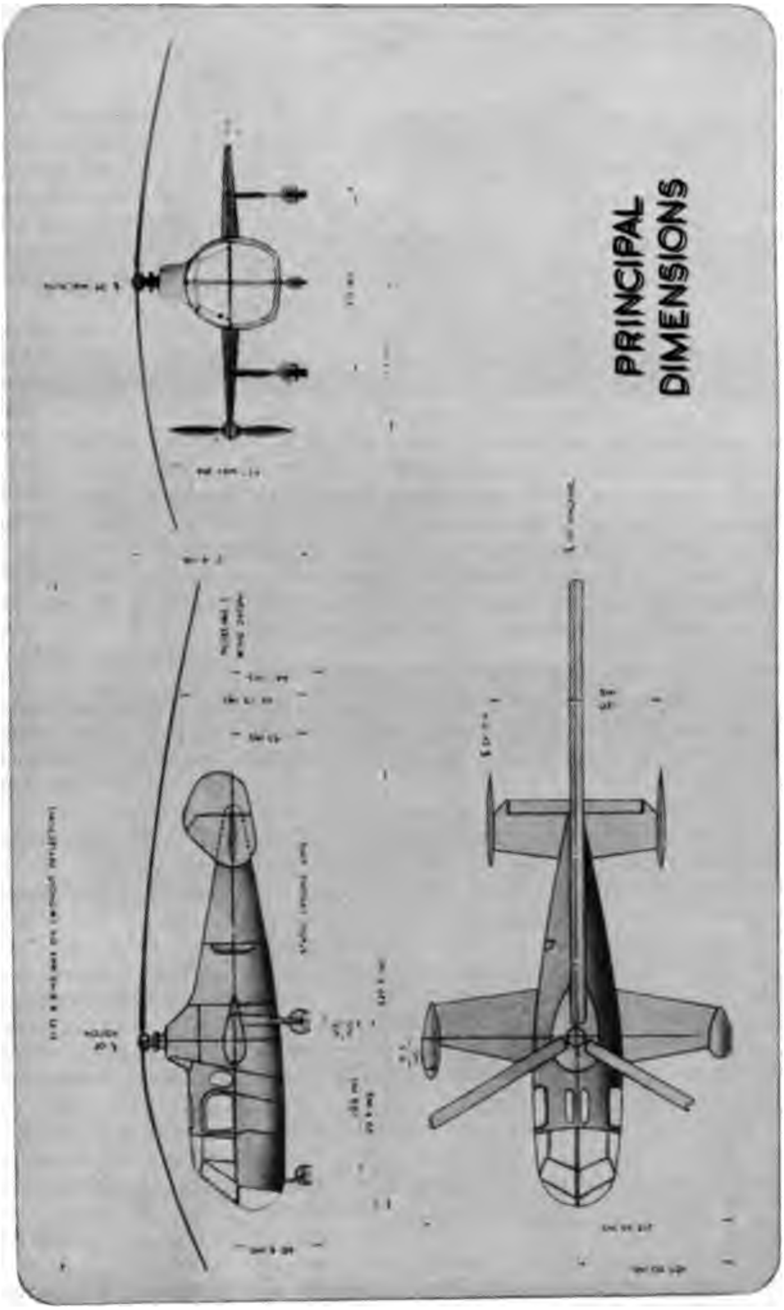


FIG. 1.

Fig. 2. Rotor Head

rotors, but, as higher-powered helicopters become available, the feature of independent propulsion as demonstrated in the Gyrodyne will become more and more essential. There are many sources of vibration inherent in rotary-wing aircraft but the periodic blade-tip stall is one which can be avoided and should not now prevent a further improvement in the helicopter speed range. Continuity of operation under adverse wind conditions is just as important for transport helicopters as for aeroplanes and can be ensured only by the ability to maintain a high cruising speed.

Control Simplification.

The simplicity of control of rotary-wing aircraft has deteriorated with the change-over from the autorotative rotor to the powered rotor. The number of controls has been increased from two to four, and the ever-present necessity for torque balance and pitch-throttle synchronisation requires that the four controls be operated simultaneously. The interdependence of so many controls, requiring continuous manual adjustment by the pilot, is a further penalty that has been paid for the ability to hover.

In the Gyrodyne an attempt has been made to minimise this penalty by the suppression of one control. There are no flight controls other than stick, throttle and rudder pedals, collective pitch change being effected automatically. The required automatic change in blade angle is associated with the angular displacement of the blade in azimuth in response to torque, by giving the drag hinge a slight downward and outward inclination. Thus, there is an immediate increase in manifold pressure whenever the throttle is opened without there being any appreciable change in angular speed. In addition to the automatic change of collective pitch, an over-riding control, mainly for trim purposes at altitude, has been designed but is not yet installed. It is proposed to utilise this also for momentary hovering prior to a power-off landing. The over-riding device operates additional blade hinges which are locked in normal flight.

A further penalty in the helicopter has been the introduction of blade torsional bearings for both collective and cyclic control of pitch. In the Gyrodyne such bearings are eliminated entirely, and instead of a separate *swash-plate* for transmitting control movements from the stick to each

individual blade through the necessary levers and bearings, the rotor head itself forms the swash-plate.

This does not mean that the hub axis is tilted as was the usual practice with autorotative rotors. Instead, the hub axis, *i.e.*, the axis of the main bearings, remains fixed, and the rotor head—the hub member to which the blades are attached—is tilted with respect to the hub axis. Consequently, in forward flight a forward inclination of the head balances the backward inclination of the tip-path plane that results from the usual flapping motion of the blades. The tip-path plane, therefore, remains substantially at right angles to the hub axis in all conditions of steady flight, which is important for minimising vibration.

Safety Measures.

Stick shake is completely eliminated by the use of hydraulic irreversibility. Except during the first few hours of flight, the steady loads also have been suppressed hydraulically, but it is now considered more desirable to retain the steady loads, which provide a natural feel, and to use hydraulic irreversibility only for suppressing stick shake and as a precaution against misuse of the control. A sudden backward movement of the stick in flight, for example, can impose on helicopters loads in excess of their design criteria.

A similar possibility exists in helicopters on initial engagement of the clutch and, in the Gyrodyne, to ensure that the rotor blades can not be damaged by a sudden angular acceleration, an electrically-operated actuator is provided for controlling the rate of clutch engagement, thus limiting the maximum starting torque. It is thought that a torque-limiting device should be an essential airworthiness requirement for helicopters.

Transmission Features.

The installation of the power plant and transmission consists of four self-contained units : the Alvis engine with its mounting and cooling system; the main gearbox incorporating the clutch and freewheel in addition to the first stage reduction gears for the rotor and propeller drives ; the top gear box, housing a double epicyclic gear, with a rotor brake mounted above it ; and, at the outer extremity of the starboard wing, a gear box carrying the propeller reduction and pitch-changing gear. The propeller is positively geared to the engine and not to the rotor.

Fig. 3.

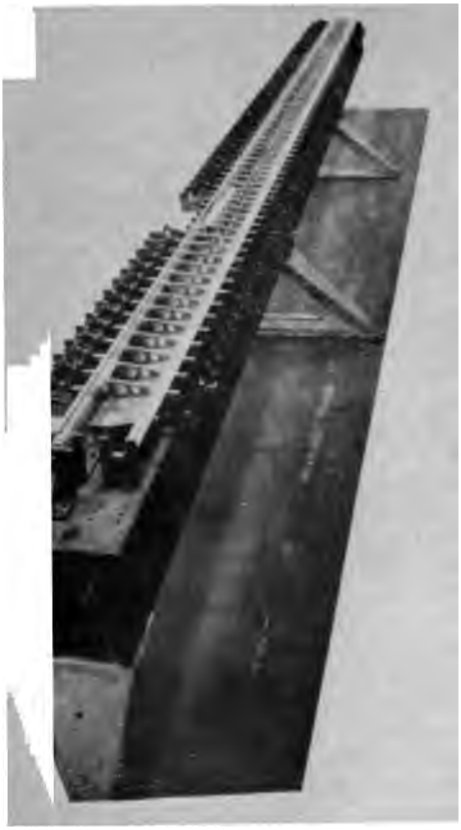
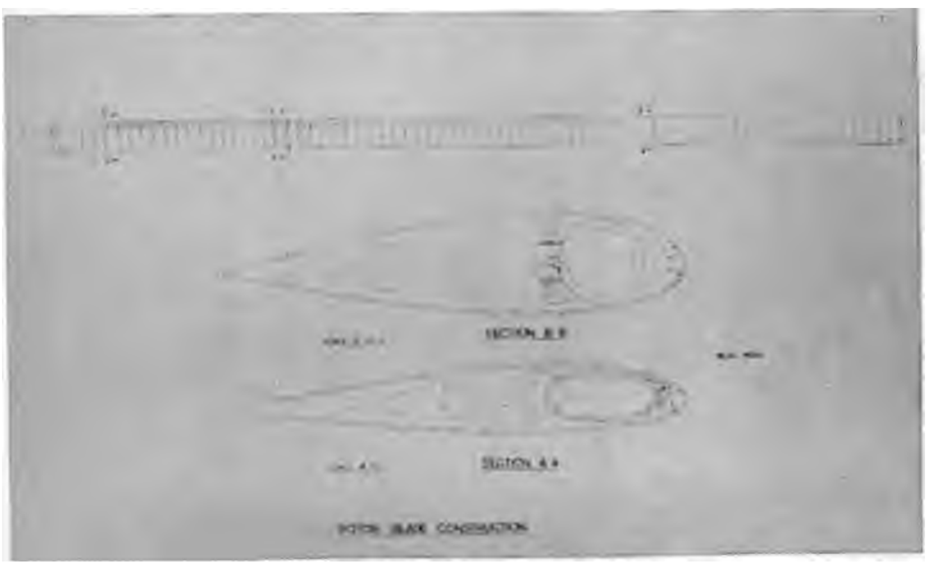


FIG. 4.—Jig for blade manufacture.

FREEDOM FROM FLUTTER AND FATIGUE.

The rotor blades are of accentuated flexibility in bending, but rigid in torsion. On no occasion has there been any sign of flutter, although a Mach number of 0.8 has been exceeded at the advancing blade tip. The blades have been manufactured to close tolerances in a jig and, with this object in view, they have been given no taper or twist. A stiff profile is maintained by wooden ribs and a plywood covering, a steel tubular spar being the main strength member. This is circular in section at the root end, but over the greater part of its length it is of oval section. A root collar integral with the spar — a Seefab development — enables the blade to be attached to the root fitting without stress concentration due to perforation of the tube. Drilling of the spar is avoided also at the rib clips which are attached frictionally over the main portion of the blade.

FIG. 5



Strain gauge tests have been conducted in flight, and the steady and alternating stresses determined at four different stations along the blade. Specimen lengths of the spar, loaded to a greater stress than the corresponding parts of the blade in flight, have been placed in a fatigue-testing machine and subjected to alternating stresses several times greater than the highest recorded in flight. The spar has thus been proved to have an unlimited life.

FUSELAGE STABILISATION.

Although the present fuselage is of steel-tube construction, a metal monocoque is being provided for production The front portion is long enough to take a full-size stretcher, and as the tail portion is relatively short, side fins are required for directional stability.

No attempt has been made so far to provide dynamic stability at zero forward speed. The necessity for automatic stabilisation of helicopters in the hovering condition depends upon whether the aircraft will be required to hover for long periods. As the Gyrodyne is designed primarily as a transport aircraft, its normal condition of flight is at cruising speed. It is, therefore, under cruising conditions that stability is important and for this purpose a tail-plane is provided in addition to the side fins. The stub wings, which form fairing surfaces for the structure supporting the propeller and the main legs of the tricycle undercarriage, have a stabilising effect in roll—a manoeuvre in which rotary-wing aircraft tend to be too sensitive, compared with aeroplanes, owing to the absence of fixed wings.

SPECIFIC UTILISATION.

In any field of transport, no one device has a monopoly of all functions. Each type is a solution of a particular transportation problem. The advent of the helicopter, for example, does not put an end to the aeroplance, but confines its operation to uses for which it is better adapted. So also every

FIG. 6.—Rotor spar fatigue tests.

Association of Gt. Britain.

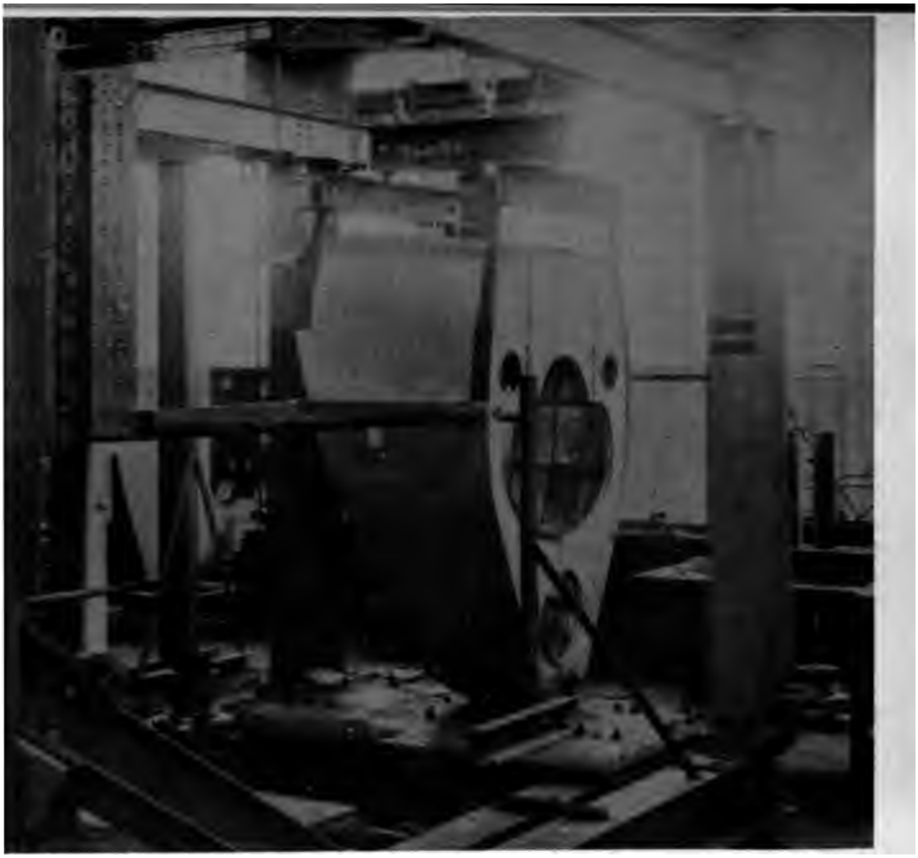


FIG. 7.

form of helicopter has its own specific sphere of usefulness, and the obvious one for the Gyrodyne is wherever a high cruising speed is essential, or continuity of operation is required under adverse wind conditions. Thus, the Gyrodyne is best adapted for making long non-stop journeys, such as from city centre to city centre, rather than as a feeder line transport for operating only between a city centre and its adjoining airport.

If the ability to hover has been combined effectively with the ability to maintain a high cruising speed, without there being an appreciable departure from the low disc-loading and low-pitch advantages of the autorotative rotor, the Gyrodyne has achieved its purpose and would appear to fulfil the general requirements of a helicopter intended for civil use.

REFERENCES :—

Ref.1. BENNETT, J. A. J. *Aircraft Engineering*, January, 1940.

Ref.2. BENNETT, J. A. J. *Journal of the Helicopter Association*, July, 1948.

FIG. 8.—The Gyrodyne in forward flight.

THE CHAIRMAN.

The second paper this afternoon is to be presented by MR. R. HAFNER and deals with some aspects of the Bristol Type 171 Helicopter. MR. HAFNER was educated at the Technical College in Vienna and has been solely engaged on rotary wing development for more than twenty years, having produced his first helicopter design in 1927. He came to England in the early 30's and continued with helicopter development and then turned his attention to the design and construction of a gyroplane which was known as the A.R.3 and which aircraft proved to be very efficient and pleasant to fly.

During the early part of the late war, he collaborated with DR. BENNETT on various rotary wing projects under the M.A.P., and joined the Bristol Aeroplane Co., as Chief Designer of the Helicopter Division in 1944 in which capacity he is entirely responsible for the design of the Bristol 171. I can speak at first hand of the excellent qualities of this aircraft having been privileged to carry out the first few hours of the prototype flying. I now ask Mr. Hafner to present his paper.

The Bristol 171 Helicopter

By RAOUL HAFNER

The technical problems confronting the helicopter designer are very clearly enumerated in Captain LIPTROT'S paper, and Wing Commander BRIE has drawn attention to a number of considerations of importance to the operator.

With some of these problems I have dealt in an earlier paper[1], and in order to avoid repetition I propose to leave out from this discussion points which have already been raised.

VIBRATION.

Rotating-wing aircraft in forward flight are subject to vibrations for reasons which are fundamental and we must not therefore expect the elimination of these symptoms but only their reduction to generally tolerable proportions. We need, therefore, more accurate methods of recording and analysing vibrations in helicopters in terms of component frequencies and amplitudes, and in addition we must have generally agreed standards for comfort, *i.e.*, limiting vibration levels as a yardstick both to makers and users of these aircraft.

As to the causes of rotor vibrations there is in the first instance a change of velocity with blade azimuth the maximum being at the advancing and the minimum at the retreating side of the rotor orbit, and secondly a change of inflow angle with blade azimuth due to the coning of the rotor blade and the curvature of the airflow in the vicinity of the rotor, the maximum being aft and the minimum forward of the rotor centre. Therefore, in order to maintain a constant rotor thrust (or constant blade lift) during rotation, which is one of the essentials for freedom from vibration, the blade incidence must be varied in a cyclic manner. Because the factors governing blade feathering are complex, the feathering motion cannot be expressed mathematically in a simple form but only by an infinite Fourier series.* Typical values for

the Fourier coefficients A_0, A_1, B_1, A_2, and B_2 for a conventional rotor are given in Figure 1 as a function of the tip speed ratio μ. A_0 represents the constant part of the blade incidence which can be obtained by the collective pitch control. A_1 and B_1 relate to the fundamental harmonic of the feathering motion which can be produced by a simple tilt of the control orbit with respect to the rotor orbit. The conventional swash plate or spider control or the tilting of the hub in an articulated rotor will produce this effect. The coefficients A_2 and B_2 relate to the second harmonic of feathering motion. For small tip speed ratios these coefficients (and those of the higher harmonics) are negligible so that the conventional rotor control which can provide a simple sinusoidal incidence variation during rotation, does satisfy to a fair degree the theoretical requirements. However, at larger tip speed ratios, the higher harmonics, which cannot be produced by the conventional control mechanisms, become predominant components. Thus at higher translational speeds the blade lift cannot be held constant any longer during rotation and vibration arises.

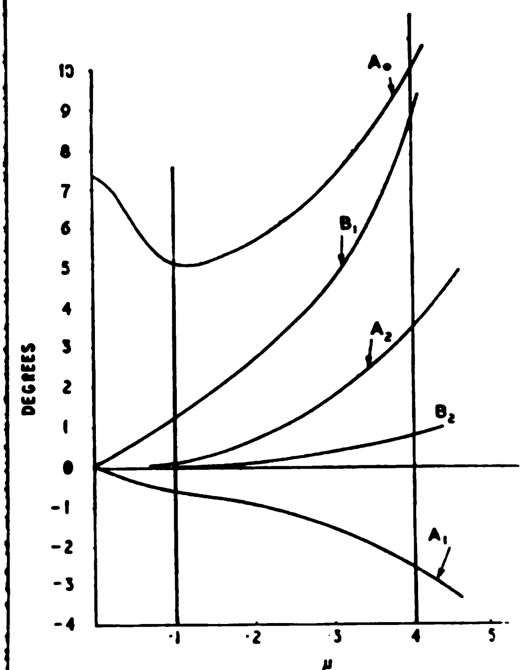


FIG. 1.

Fourier coefficients of feathering motion for conventional helicopter rotor in level flight.

$\theta = A_0 - A_1\cos\psi - B_1\sin\psi - A_2\cos 2\psi - B_2\sin 2\psi - \ldots$

One can, of course, think of mechanisms which are capable of producing cyclic movements of a more complex form including the higher harmonics referred to above. The mechanical elaboration involved in any such scheme is, however, considerable and in my opinion prohibitive and I regard therefore as a practical limit for conditions of rotating wing flight the tip speed ratio μ_{lim} where higher harmonics just become noticeable.

The question arises thus. Can the Fourier coefficients be controlled by suitable design parameters and other means, with a view to suppressing

*Blade pitch $= \theta = A_0 - A_1 \cos\psi - A_2 \cos 2\psi$
$- B_1 \sin\psi - B_2 \sin 2\psi +$ higher terms in ψ

A list of those symbols not defined in the text will be found at the end of the paper.

the higher harmonics over as wide a range of μ as possible? As already mentioned non-linearity and indeed discontinuities in the functions governing blade feathering are the principle causes for the higher terms, which I propose to discuss briefly.

The following assumptions are made :—

1. The resultant of the blade lift is acting at approx. $\frac{3}{4} R$.
2. The blade must be substantially free from stall outboard of this point. If the mean lift coefficient during hovering (Ref. 2) is

$$C_{L\,basic} = \frac{\text{Blade Lift}}{\frac{1}{2}\,\rho\,\omega^2 \int_0^R c r^2\, dr}$$

then the lift coefficient in translational flight can be shown to be

$$C_L = C_{L\,basic} \times F$$

$$\text{where} \quad F = \left\{ 1 + (\mu/\tau)\ \sin\psi \right\}^{-2}$$

$$\text{and } \tau = r/R$$

F reaches a maximum when the blade is retreating, *i.e.*, (taking $\tau = \frac{3}{4}$)

$$F_{(\psi = 270^\circ)} = F_{max.} = \left\{1 - \tfrac{4}{3}\,\mu\right\}^{-2}$$

and a limiting condition is therefore obtained when

$$C_L = C_{L\,basic} \left\{1 - \tfrac{4}{3}\mu\right\}^{-2} = C_{L\,max.}$$

$$\text{or} \qquad \mu_{lim} = \tfrac{3}{4}\left(1 - \sqrt{\frac{C_{L\,basic}}{C_{L\,max.}}}\right)$$

A high tip-speed ratio can therefore be obtained only where the blade is flying at a low basic lift coefficient with an aerofoil capable of producing a high $C_{L\,max.}$

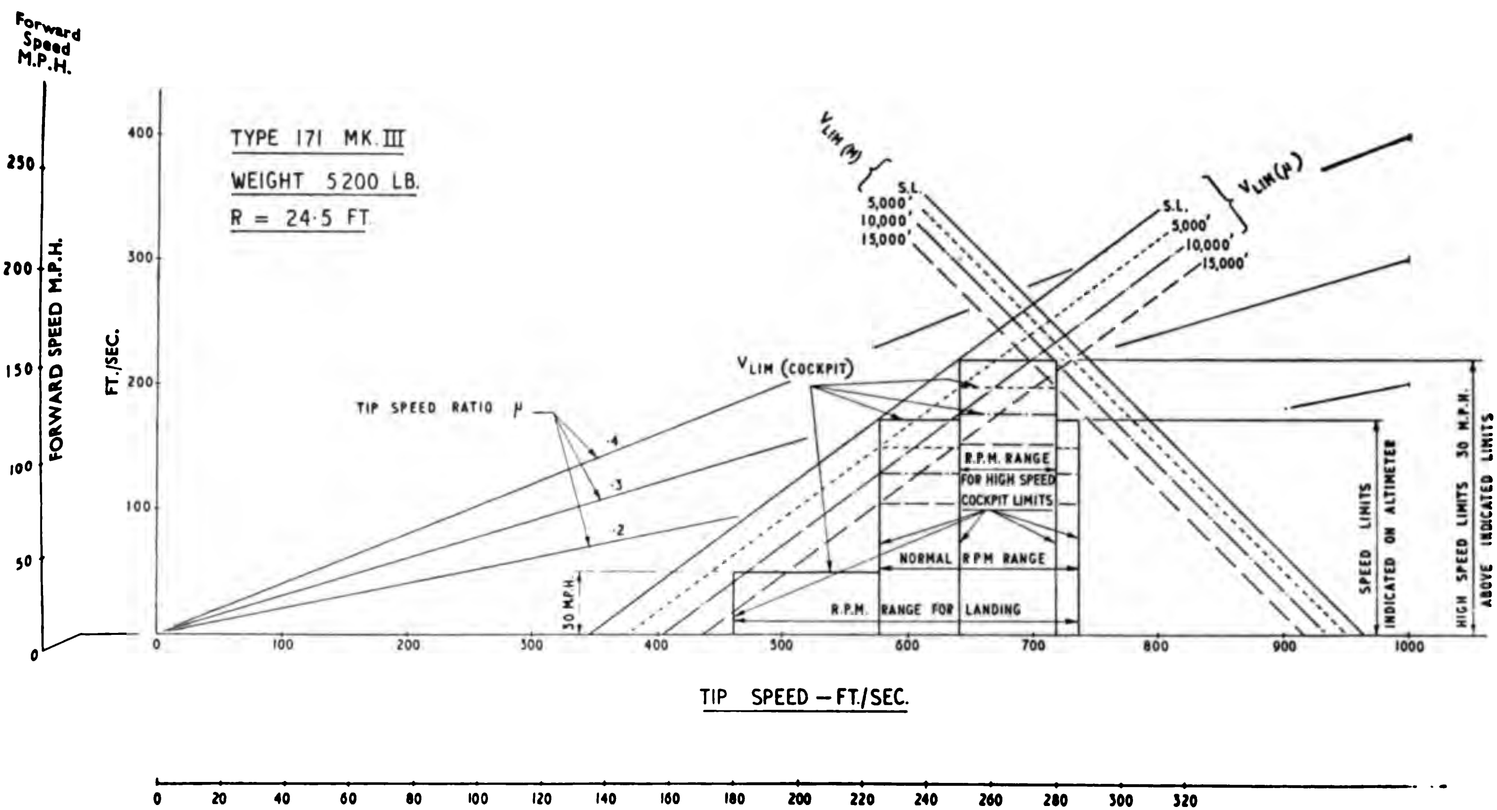
The above expression can be written in another form, *viz.* :

$$V_{lim\,(\mu)} = \tfrac{3}{4}\,(V_T - V_{T\,min.})$$

where $V_{lim\,(\mu)}$ = limiting translational speed ($\mu_{lim.}$)
V_T = $R\omega$ = blade tip speed
$V_{T\,min.}$ = the minimum blade tip speed when $C_{L\,basic} = C_{L\,max.}$

$V_{lim(\mu)}$ for the rotor of the Bristol Helicopter 171 Mark 3 is given in Figure 2 for various altitudes. In the same graph is similarly shown a high speed limitation $V_{lim.(M)}$ which represents the critical Mach No. for the airfoil near the blade tip. An airfoil with a low t/c ratio (below 10%) is obviously desirable in this region, in order to delay shock stall.

The area within the limits shown in Figure 2 can be utilized by the flight envelope of the rotor, which is, of course, subject to such additional limitations as may be determined by strength considerations or operating conditions of the power unit, etc. The rotor flight envelope is defined in the cockpit by a very wide r.p.m. range for landing purposes which applies to speeds below 35 m.p.h., a smaller normal r.p.m. range applicable up to the speeds indicated on a special scale on the altimeter, and a narrow r.p.m. applicable up to the maximum speed and for flight manoeuvres involving high normal accelerations.



Forward Speed M.P.H.
FORWARD SPEED M.P.H.
FT./SEC.
TYPE 171 MK. III
WEIGHT 5200 LB.
R = 24·5 FT.
TIP SPEED RATIO μ
·4
·3
·2
V LIM (COCKPIT)
V LIM (M)
V LIM (μ)
S.L.
5,000'
10,000'
15,000'
R.P.M. RANGE FOR HIGH SPEED COCKPIT LIMITS
NORMAL RPM RANGE
R.P.M. RANGE FOR LANDING
30 M.P.H.
SPEED LIMITS INDICATED ON ALTIMETER
HIGH SPEED LIMITS 30 M.P.H. ABOVE INDICATED LIMITS
TIP SPEED — FT./SEC.
ROTOR R.P.M.

FIG. 2.

The above considerations relate to blade lift. There is in addition the problem of maintaining constant the force acting on the blade in the plane of rotation. This force is made up by the profile drag of the blade and a small component of the lift vector due to the airflow through the rotor.

The profile drag of the airfoils of the type used in rotor blades can be expressed by a single curve giving $E_p \, C_{L\,max.} / C_{D\,min.}$ as a function of $C_L / C_{L\,max.}$ where $E_p =$ (profile drag)/(lift) and which is shown in Figure 3. Thus as C_L varies with ψ as the expression

$$C_L = C_{L\,basic} \left\{1 + \tfrac{4}{3}\mu \sin\psi\right\}^{-2}$$

there will be accordingly a variation of profile drag during revolution. In the upper part of Figure 3 are given as a function of μ the maxima and minima of F. From this can be obtained with the aid of the straight lines $C_{L\,basic} / C_{L\,max.}$ the range $C_L / C_{L\,max.}$ covered during revolution which in turn indicates the variation of E_p.

This figure clearly shows the following significant features

1. $F_{max.}$ increases very rapidly with μ whilst $F_{min.}$ decreases only moderately.
2. A very low " basic " lift coefficient will produce excessive drag at the advancing blade ($F_{min.}$) and a high $C_{L\,basic}$ excessive drag at the retreating blade ($F_{max.}$). In view of the statement under (1) the latter is more likely to arise and therefore it is generally safer to fly at a low $C_{L\,basic}$.
3. A low $C_{D\,min.} / C_{L\,max.}$ is beneficial all round.

The component of lift in the plane of rotation D_L is dependent (Ref. 1) on the inflow angle $v_n / v_{eff.}$, where v_n is the component of velocity normal to the plane instantaneously containing the rotor blade; and $v_{eff.}$ is the component, in the plane instantaneously containing the blade, and perpendicular to the longitudinal axis of the blade.

$$D_L = \text{(Blade lift)}. \quad v_n / v_{eff.}$$

$$= L \left\{ \frac{\tfrac{4}{3}(\lambda + \iota) + (\tfrac{4}{3}\mu\beta_0 + \zeta\iota)\cos\psi}{1 + \tfrac{4}{3}\mu\sin\psi} \right\}$$

where μ, λ and ι are the ratios between blade tip speed and forward speed, axial speed and induced speed at the rotor respectively.

ζ is a factor related to the curvature of the induced flow at the rotor.

β_0 is the coning angle of the rotor

L is the blade lift.

and τ has been taken to be $\tfrac{3}{4}$

The above expression can be written as a series as follows :

$$D_L = L \left\{ \tfrac{4}{3}(\lambda + \iota)(1 + 8\mu^2/9) + (4\mu\beta_0/3 + \zeta\iota)(1 + 8\mu^2/9)\cos\psi \right.$$
$$\left. - \tfrac{16}{9}(\lambda + \iota)\mu\sin\psi + \text{higher terms in } \psi \right\}$$

In this only the first term is constant, the others change with ψ and thus represent varying forces. It is therefore desirable that the coefficients preceeding cos ψ and sin ψ be kept as small as possible. μ, λ and ι can be reduced by increasing tip speed. λ moreover can be reduced by reducing the parasitic drag of the whole aircraft. Apart from such minor variations however λ in the pure helicopter is essentially an expression of flight condition of the aircraft, being necessarily larger in a climb than in a level flight. In an auto-rotating rotor λ is always negative. ζ cannot be controlled materially by design.

In order to illustrate the above arguments the drag of a rotor blade of the Bristol Type 171 is now analysed on the basis of the above formulae.

Conditions of flight :

Steady level flight at sea level.

Forward speed = 136 m.p.h. = 200 ft. per second.

Rotor speed = 260 r.p.m. = 670 ft. per second.

$\mu = 0.30$. $\lambda = 0.20$. $\iota = 0.0043$. $\beta_0 = 0.065$. $\zeta = 0.8$.

$C_{L\,basic} / C_{L\,max.} = 0.37/1.30 = 0.285.$

$C_{L\,max.} / C_{D\,min.} = 180.$

In Figure 4 the various components of blade drag are plotted as a function of ψ and it is shown how by a suitable choice of design parameters the drag variation due to inflow conditions $(\lambda + \iota)$ can be counteracted by profile drag (E_p). Where the latter is a maximum the former reaches a minimum and vice versa. This has been achieved by the use of a low "basic" lift coefficient giving an E_p – curve variation in the form of a positive

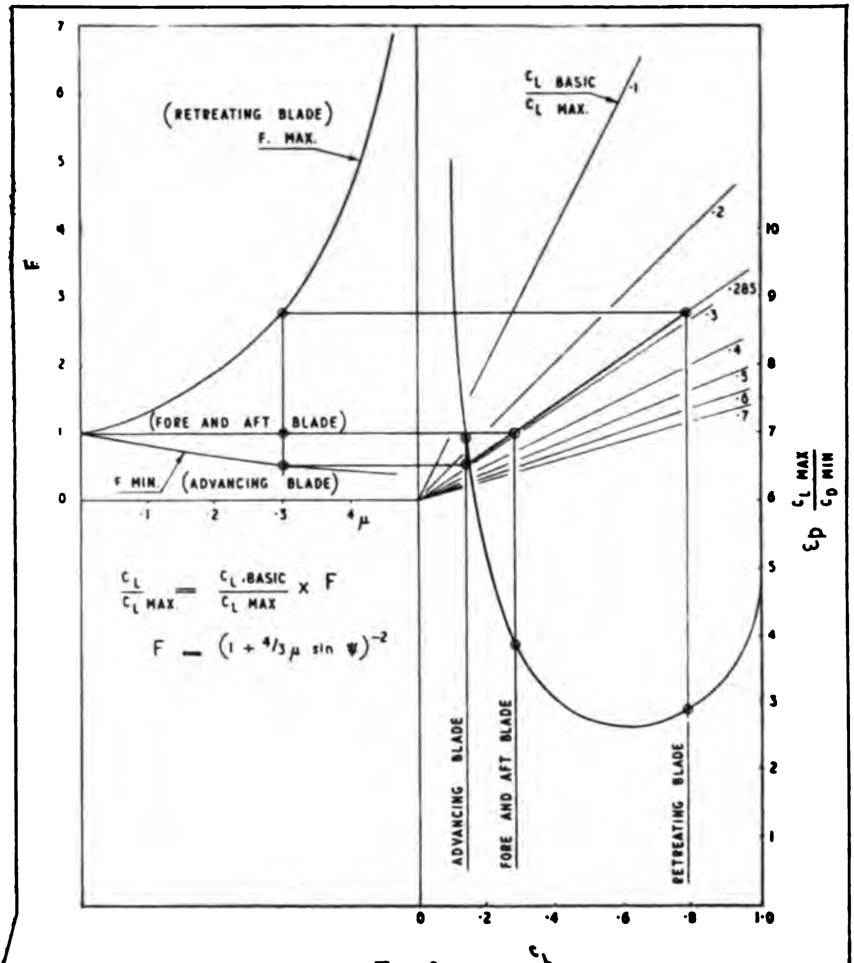


FIG. 3.

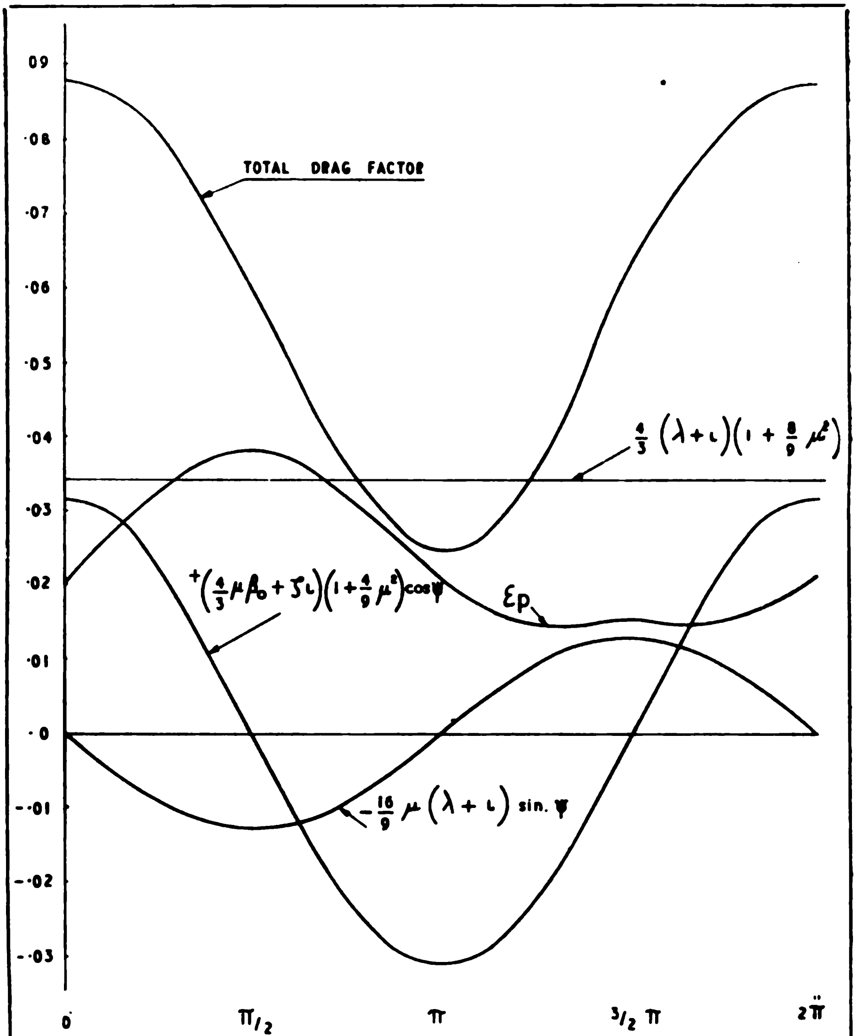


FIG. 4.

sine curve. On the other hand had the " basic " lift coefficient been high then the E_p – curve would have taken the shape of a negative sine curve thereby amplifying the variation caused by $(\lambda + \iota)$. A low " basic " lift coefficient moreover represents a safety margin against stalling in accelerated flight conditions.

It will be seen therefore that variation of blade drag is mainly caused by blade coning. This variation even with the exceptionally small coning angle of the Bristol 171 rotor represents more than 50% of the total mean drag which illustrates the importance of this design parameter. Under cruising conditions this drag variation is much more serious than the variation in blade lift referred to earlier.

The drag of all blades add up vectorially to the total rotor force in the plane of rotation. Thus the more blades in a rotor the steadier will be this force so that the 3-bladed rotor from the vibration point of view is very much better than the 2-bladed rotor which, as already mentioned earlier (Ref. 1) is only justified in the very small sizes. I have indicated too my preference for individual blade articulations over a flexibly mounted rotor (except for small sizes) as well as certain features in blade design such as careful distribution of blade mass radially as well as chordwise and a high torsional stiffness. The ideal blade tapers from root to tip in thickness and plan form, and is of metal monocoque construction.

Controls.

There is clearly a need for simplification of controls. More simplification in engineering generally means more efficiency and more safety. This argument, however, does not apply to the *number* of flying controls in the cockpit which is determined only by the degree of freedom of movement of the aircraft (Ref. 1). I am of the opinion that the conventional arrangement consisting of yawing control, rolling and pitching (or azimuth) control and vertical (or collective pitch) control together with the rotor speed control represents an absolute minimum. There is, however, ample opportunity for simplification in the mechanism of the control circuits and this has been made a fundamental feature in the design of the Bristol Helicopter. It is noteworthy that the rotor control mechanism of this aircraft (commencing at the 3 blade levers and terminating at the dual azimuth and collective pitch control levers) consists of only 27 moving parts. The use of the tie rod in this helicopter is now well known and needs no further comment.

The design of cockpit controls is at present handicapped by the lack of agreement on control layout for helicopters. Standardization of cockpit controls is an urgent need.

Stability.

I propose to make to-day only a few general observations on this subject. The stability of present day helicopters is far from satisfactory and " the " solution of the problem which must be simple as well as adequate does not appear to be around the corner yet.

There are two distinct types of stability, distinct from the theoretical as well as the pilot's point of view.

Stability in forward flight.

In this respect the helicopter does not differ materially from the fixed wing aircraft. Most of the flying time is accumulated in forward flight and therefore positive stability in this condition will prevent pilot's fatigue and therefore increase safety.

Hovering Stability.

The hovering stability is based on different principles and is more difficult to obtain than stability in translational flight. As hovering flight is carried out in circumstances when concentration on the part of the pilot is needed in any case because of the proximity of the ground or the need to *remain in* a given attitude with relation to a fixed point, and the time spent

in this condition is comparatively short, there would not seem to be the same need for positive hovering stability as for positive forward flight stability. If the latter is fully achieved whilst in hovering the aircraft is not unduly unstable, in my opinion a good advance is made on the way towards the ideal.

The Bristol Type 171 shows in forward flight a fair measure of positive stability in pitch, yaw and roll and has been flown in gusty air for extended periods without touching of any controls. Minor displacements are damped out and only severe gusts require corrective action on the part of the pilot. This has been achieved mainly by a fuselage carrying a small tailplane outside the rotor disc and a rotor with a large moment of inertia providing damping in pitching motion.

SAFETY.

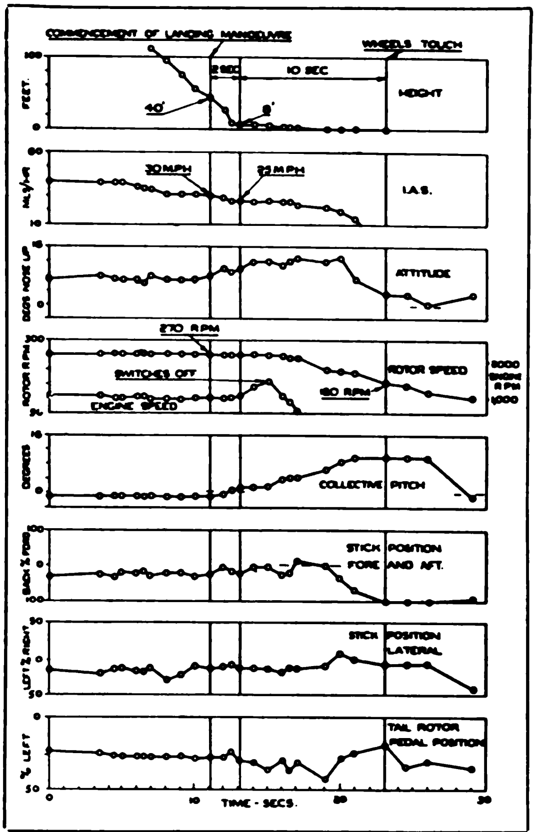
Apart from structural and mechanical safety an important safety criterion is the emergency landing in the event of power failure. Whilst the rotative wing is reputed to offer a high measure of safety in auto-rotative descents, recent reports have drawn attention to so called " danger zones " from which an auto-rotative landing could not be made without damage to the helicopter. The vertical velocity of a conventional helicopter during auto-rotative descent, especially at low forward speeds, is too great to be absorbed by the undercarriage and must therefore be checked prior to landing by momentary increase of rotor lift which involves a certain amount of energy. In the absence of engine power such energy is available in the form of kinetic energy from the horizontal velocity component of the aircraft as well as from the rotational velocity (useful r.p.m. range) of the rotor. When these two sources of kinetic energy are insufficient to provide the required check then damage will result on landing. In order to eliminate this hazard, the rotor of the Bristol Helicopter has deliberately been designed to give a high rotational moment of inertia in conjunction with an unusually wide r.p.m. range. The kinetic energy which is stored in this rotor at maximum permissible rotor speed is 680,000 lb. ft. which represents an amount of work equivalent to about four seconds hovering in the ground cushion at full load. Many landings have already been made with this aircraft with its engine switched off, which have indicated an ample supply of kinetic energy during the landing manoeuvre.

Auto-observer records of such a landing are reproduced in Fig. 5. The steady conditions during the auto-rotative descent prior to the landing manoeuvre appear to be as follows :—

Rate of descent	..	1,600 ft./min.	Engine Speed	..	Idling
I.A.S. ..	..	35 m.p.h.	Collective Pitch	..	0 degrees
Rotor Speed	..	270 r.p.m.	All-up Weight	..	4,740 lb.

At about forty feet from the ground the collective pitch is increased slightly and the engine switched off. This results after about two seconds in a checking of the descent at a height of approximately eight feet, and a reduction of forward speed by some five miles per hour. During the following ten seconds the aircraft sinks slowly until, at first the tail skid, and then the wheels touch down. During this period the collective pitch is steadily increased to 11°, the rotor speed drops to 160 r.p.m. and the forward speed down to walking pace. Apart from an aft movement of the control column

Association of Gt. Britain.



at touch down, all controls remain substantially stationary. This serves to show that with sufficient kinetic energy and good control, an engine-off landing can be made in safety and comfort, even with a heavy helicopter.

FIG. 5.

Auto-observer records of typical auto-rotating landing of Bristol Helicopter Type 117.

CAPITAL AND MAINTENANCE COSTS.

One of the main arguments against the helicopter is that it is expensive to buy and an excessive amount of time and money is spent on its maintenance.

The helicopter of to-day is expensive to buy not for reasons peculiar to this type of aircraft but simply because the market to-day does not justify production on a large scale, without which a material reduction of price cannot be achieved.

Maintenance costs can be reduced if the following design principles are adhered to :—

1. Mechanical simplicity and economy in the number of moving parts.
2. Fatigue resistance and high life factors in parts subject to cyclic forces and to wear.
3. Accessibility.
4. Interchangeability.

Figure 6 shows the entire mechanical assembly of the Bristol 171 helicopter which comprises the power unit with clutch, cooling fan, and cowlings, the main rotor gearbox and hub carrying the main rotor blades, the tail rotor gearbox and hub carrying the tail rotor blades and transmission shafts between these units and in addition the rotor controls. The extreme simplicity of this layout is evident.

FIG. 6

It has been possible to design all wearing parts for a life of 7,500 hours without great sacrifice in weight. This feature apart from beneficially affecting the safety of the aircraft will it is hoped eventually permit the periods between overhauls to be increased to 1,000 hours or more, (excepting the power unit) which not only simplifies maintenance but ensures that the adjustment of wearing parts is left undisturbed over long periods which allows these parts to run-in under ideal conditions.

Fatigue is one of the topics in aircraft engineering. There is no royal road to endurance and a long and generally arduous test and development programme with the proverbial " exploring of every avenue and leaving no stone unturned " which involves a great amount of test equipment and cost is the only real safeguard against fatigue failures. Special testing equipment which has been developed in conjunction with the Type 171 has been discussed in an earlier paper (Ref. 1).

The principle of interchangeability is, of course, applied generally. We hoped originally to build individually interchangeable rotor blades which

FIG. 7. The Bristol 171 Helicopter in flight.

were to be balanced dynamically as well as aerodynamically against a master blade, but experience to date has indicated that blades can be assembled satisfactorily only in rotor sets. This does not, however, in the event of damage to one blade in a rotor, imply the scrapping of the remaining good blades which can be "paired" with others to make up new rotors.

My acknowledgements are due to the Ministry of Supply and The Bristol Aeroplane Co., for permitting the publication of information relating to the Bristol Helicopters Types 171.

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SYMBOLS.

V	=	Forward velocity of helicopter.
ω	=	Rotor angular velocity.
r	=	Radial distance of blade section, measured from hub.
R	=	Rotor tip radius.
μ	=	Tip speed ratio = $V/\omega R$.
ψ	=	Blade azimuth angle measured in direction of rotation from downwind position of blade.
β_0	=	Rotor coning angle.
ρ	=	Air density.
$C_{L\ max.}$	=	Maximum lift coefficient of blade before stalling.
$C_{D\ min.}$	=	Minimum profile drag coefficient of blade.

THE CHAIRMAN.

The last paper this afternoon is to be read by MR. J. S. SHAPIRO, and is a description of the Cierva helicopter Type W.11, popularly known as the "Air-Horse." MR. SHAPIRO is a graduate in Mechanical Engineering of the Swiss Polytechnic and an A.F.R.Ae.S. and had varied experience in the design of ancillary aircraft equipment in France before coming to this country in 1940. He was then for a time with Power Jets Ltd., after which he had further experience on design of aircraft instruments and power assisted aircraft controls. In 1943 he joined the Cierva Autogiro Company and is now Senior Technical Officer to that firm.

Unlike the other two aircraft you will have heard described to-day, the Cierva W.11 has not yet flown, but has done a good deal of preliminary ground running and it is hoped that it will take the air in the very near future. I will now ask MR. SHAPIRO to read his paper.

The Cierva "Air Horse"

By J. S. SHAPIRO, DIPL. ING., A.F.R.Ae.S.

As my contribution to this afternoon's proceedings, it is my task to give you a brief account of the Cierva " Air Horse." This machine has the distinction of being the world's largest helicopter undergoing flight testing.

Following the recent S.B.A.C. exhibition at Farnborough, I have heard many kind and unkind expressions of expert and inexpert opinion, but the lowest common denominator seems to be that it is an " astounding contraption." Faced with this challenge, my purpose this afternoon is somewhat apologetic, namely, to show that it is neither astounding nor a contraption. In fact, we, in the Cierva Autogiro Company, have persuaded ourselves that God decreed three rotor helicopters. All others are merely attempts by men to cheat His divine laws.

The " Air Horse " design arose primarily as an answer to the demand for large loads. It was realized that difficulties in helicopter construction. increased in proportion to rotor diameter and nothing was therefore more natural than to increase the number of rotors.

It is not surprising, however, that three rotors were chosen. A body in space is determined by the position of three of its points provided these are not in line. The three rotor conception is therefore natural and as such

can be traced back to early origins. Fig. 2 shows a patent drawing from a specification of FLORINE (1921) which covers the torque compensation by rotor tilt in a co-rotating multi-rotor helicopter.

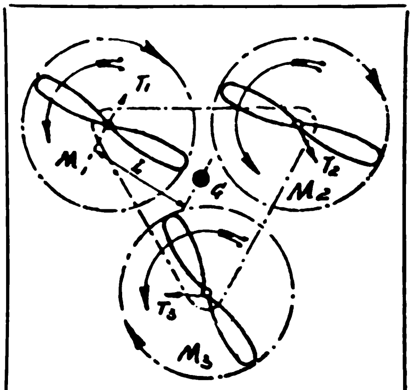
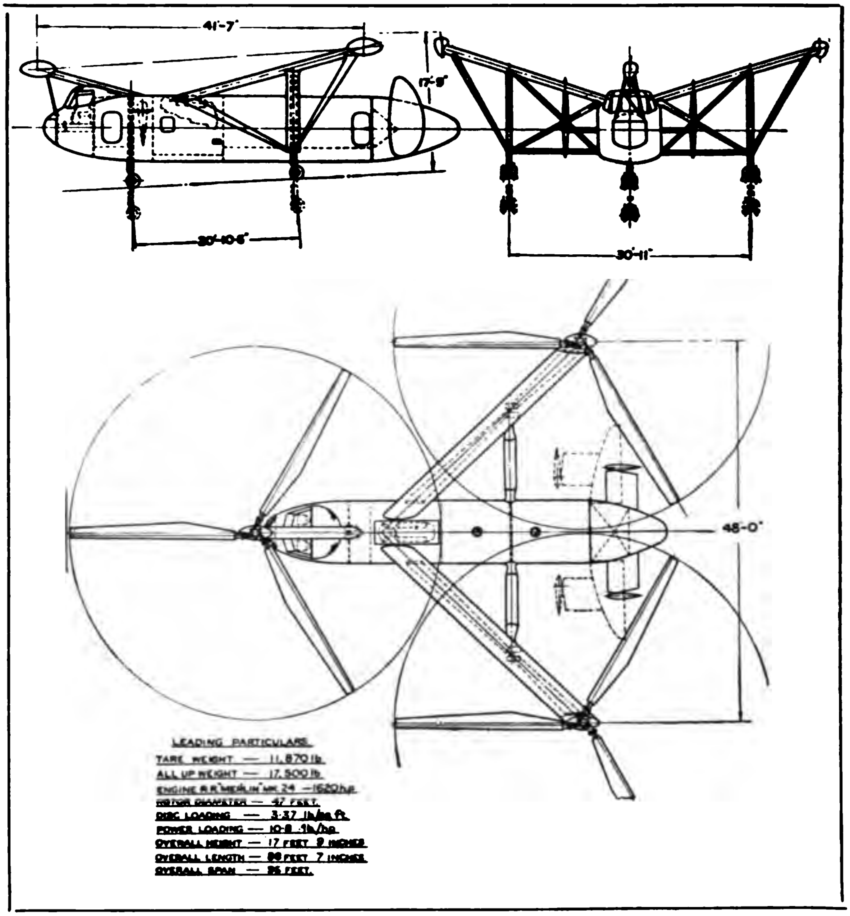


FIG. 2. FACSIMILE.

FIG. 3.
G.A. OF W.II
"AIR HORSE."



Distinguishing Features.

Time does not permit me to dwell upon the logical development of the extensive design investigations which gradually led to the specific features of this machine as it has finally emerged. These distinguishing features, in combination, render a novel conception. Contrary to Florine's proposals, the "Air Horse" rotors have freely flapping blades, but in common with Florine's ideas, the rotors rotate in the same direction and torque reaction is counteracted by horizontal thrust components. These are obtained through a built-in tilt of the rotors mainly in the lateral sense.

This machine is further characterized by a single rotor being placed forward, in the normal direction of flight, with the remaining two rotors, in side by side formation, behind. It is controlled about its pitching and rolling axes by means of lift couples obtained through differential application of collective pitch to the three rotors in an obvious manner. For the purpose of control about the yawing axis cyclic pitch variation in the fore and aft phase is applied differentially to the side by side rotors. The result of this is a virtual fore and aft tilt of the rotor discs, thereby establishing horizontal thrust components with a yawing couple between them.

Finally, the machine is fitted with an undercarriage having a stroke of five feet and is thereby enabled to absorb the shock of very high rates of descent.

W11 PRINCIPAL DATA.

ALL UP WEIGHT	17.500 LB
EMPTY WEIGHT (FREIGHT CARRIER)	11.870 LB

ROTORS

NUMBER	3
DIAMETER	47 FT.
NUMBER OF BLADES PER ROTOR	3
NOMINAL SOLIDITY	0·0598
NOMINAL TWIST	11° 45′
NOMINAL TAPER	2·584 : 1
BLADE PROFILE	N.A.C.A. 23015
NOMINAL R.P.M.	219·5

ENGINE.

1 ROLLS-ROYCE - MERLIN - MK 24
SUPERCHARGER SINGLE STAGE TWO SPEED
GEAR RATIOS 8·15 : 1 AND 9·49 : 1

	BOOST	R.P.M	I.C.A.N SEA LEVEL H.P.
MAX POWER (5 MIN)	+18	2.850	1.620
CLIMB POWER (1 HOUR)	+12	2.850	1.290
MAX CONTINUOUS POWER	+9	2.850	1.120

PERFORMANCE

MAX. RATE OF VERTICAL CLIMB, I.C.A.N. SEA LEVEL CONDITIONS = 900 FT/MIN.

LEVEL FLIGHT SPEED FOR MAX CONTINUOUS POWER I.C.A.N. SEA LEVEL CONDITIONS = 125 M.P.H

Fig. 4.

Description.

Of all the design details of this machine, I have to restrict myself this afternoon to the essence of the control system. The hub control

mechanism terminates in the actuating sprockets of which the lower, causing axial displacement of a hub control spider, varies the collective pitch of the blades, and the upper, by tilting the hub control spider, imposes upon the blades a cyclic pitch variation of fixed azimuth.

Each collective pitch sprocket of a rotor is connected through a cable transmission to one extremity of a stationary spider in the fuselage and each of the cyclic pitch sprockets is actuated through a similar transmission by the displacement of the extremities of another stationary spider. The two stationary spiders are the heart of the " control exchange " mechanism, and are shown in Fig. 5 in diagrammatic form. Axial and tilting movements of the " exchange " spiders combine to control the actuating sprockets in the hub. The pilot's control organs are linked with the " exchange " spiders so as to produce the correct combinations of common and differential

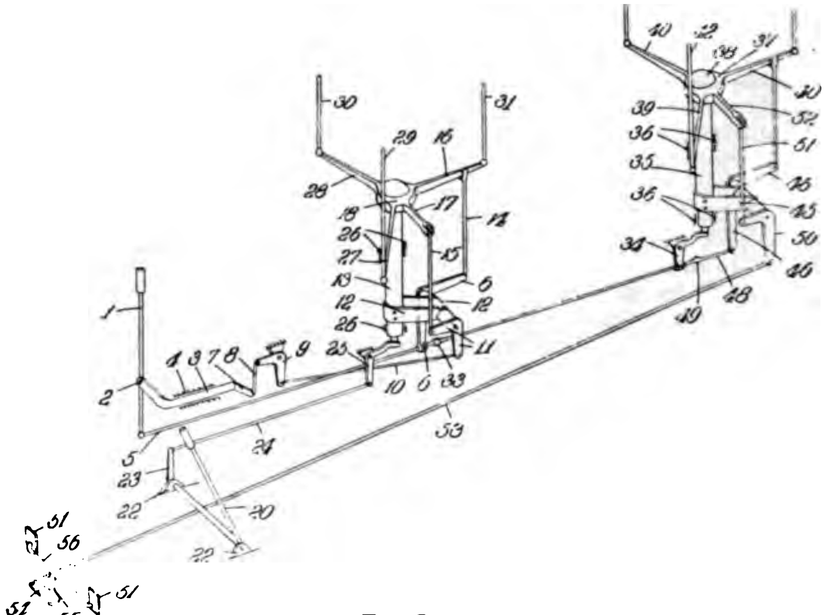


FIG. 5.

increments of collective and cyclic pitch control. This linkage is assisted by hydraulic jacks supplied by Messrs. Lockheed under the trade name of " Servodyne."

Basic control functions, consist of the following. Raising and lowering the " collective exchange " spider by means of the pitch lever produces common collective pitch change. The pilot's control column communicates tilting motion about the pitching and/or rolling axes to the " collective exchange " spider which causes differential variation of collective pitch (and lift) between the rotors.

Finally, the rudder pedals impose a tilting motion on the " cyclic exchange " spider about its rolling axis which causes the tip path planes of the two rear rotors to be differentially tilted in the fore and aft sense thereby producing a couple between the opposing horizontal thrust components.

Development of Controls.

With controls connected as described so far, the machine is fully controllable, but to extend its range of forward speeds and to improve its flying qualities further control connections are being gradually introduced which are considered in order of importance.

In forward flight at any appreciable speed it becomes essential to reduce or suppress the flapping of the blades. To this end all rotors must receive cyclic pitch control in the same sense and roughly of equal magnitude. This task is carried out by imposing an axial displacement on the " cyclic exchange " spider whenever fore and aft movement of the control column takes place. The interlinkage is adjusted for suppression of flapping in level flight. Nearly complete suppression of flapping is easily performed by a linear interlinkage. This interlinkage is made possible by a definite relation between stick position and forward speed such that the stick is maintained in a position further forward for increased speed. Reference will be made later to this feature, which is illustrated in Fig. 6. (Based on " variable dihedral " as explained below).

Directional trim is provided for use in forward flight by means of orientable fins under the control of a trimmer wheel operated by the pilot. This serves to avoid holding off the rudder pedals during long stretches of level flight.

The stability characteristics of a three rotor helicopter are greatly influenced by the amount of " dihedral " between the rotor discs. Effective dihedral is determined not by the mechanical axes but by the virtual axes, normal to the plane referred to which no cyclic pitch change takes place. It has been found that negative dihedral contributes to dynamic stability in hovering whilst " stick fixed " stability in forward flight requires positive dihedral. This conflict can be resolved through the introduction of variable dihedral by means of a gradual fore and aft tilt of the " cyclic exchange " spider thereby producing virtual differential tilt between the front rotor, on the one hand, and the two rear rotors on the other. Dihedral variation will also be interlinked with fore and aft movement of the control column. (Fig. 6).

It is intended to provide an interlinkage between the common pitch lever and the directional controls so as to ensure yawing equilibrium throughout the range of rotor r.p.m. in flight.

It will be appreciated that whilst most of the specific features of the " Air Horse " are based on well known principles the number of possible combinations is very large and the selected combination has been evolved through a long process of elimination.

Claims.

The " Air Horse," by virtue of its configuration and distinguishing features enjoys many inherent advantages some of which are as follow.

Control and Stability. The control of the aircraft in roll and pitch is extremely powerful in the sense that only a small fraction of available control range is required to obtain angular accelerations above those common in present-day helicopters. Furthermore, control couples are nearly " pure " and not associated with horizontal forces until the aircraft has actually changed its attitude in response to the application of control. Both features are due to the fundamental method of multipoint control and cannot be equalled in a single rotor helicopter.

In the three rotor machine the basic control functions of pitching and rolling are produced by increments of lift and not by the lift itself. An increment of lift can always be obtained by blade pitch variation even when the lift itself is going through zero. It can be said, therefore, that basic control functions are operative in three rotor machines under all conditions of flight, without exception.

The direct significance of stability concepts in helicopters is as yet uncertain, but in some respects a three rotor (or tandem) helicopter is more similar to the fixed wing aircraft than the single rotor helicopter. Static stability in the " original " sense is influenced by the horizontal position of the centre of gravity relative to the geometric centre of the lifting surfaces though the vertical C.G. distance has a great de-stabilizing influence in a helicopter but not necessarily in fixed wing aircraft. There is, however, one

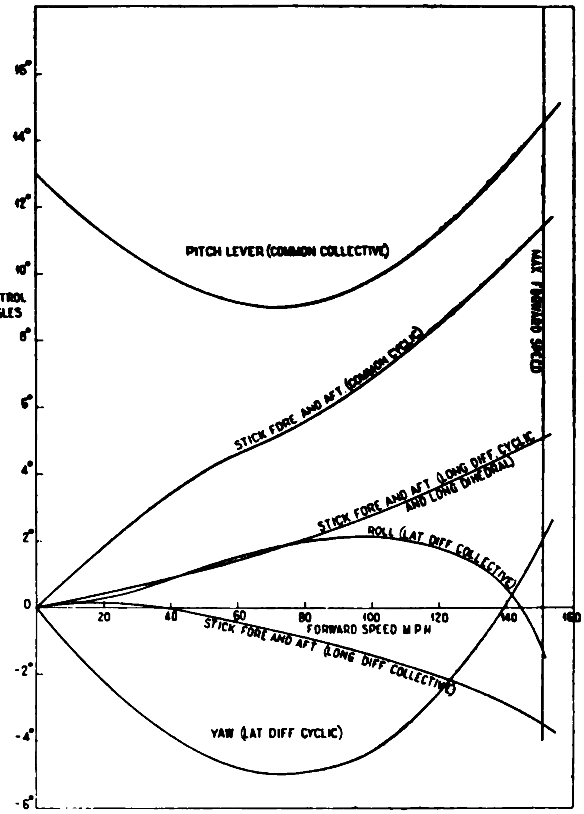


FIG. 6.

" AIR HORSE "

LEVEL FLIGHT

CONTROL

CHARACTERISTICS.

fundamental difference between the " Air Horse " and a fixed wing aircraft. The " stick fixed stability " in the three rotor helicopter depends almost entirely on the longitudinal dihedral between the front rotor and the rear rotor pair. The two " stabilities," therefore, are independent. In the " Air Horse " both are positive *throughout the speed range.*

$\delta M / \delta u$ is made negative (conventionally denoting positive stability) by placing the centre of gravity forward of the geometric centre of the rotors

by 8% of the distance between the front rotor and the line joining the rear rotors. This amount covers the de-stabilizing influence of interference between front and rear rotors in forward flight as well as the de-stabilizing effect of the vertical distance between the C.G. of the aircraft and the plane of the rotors, the latter being approximately three times as severe as the former. It is assumed that the instability of the fuselage body is fully balanced by its own tail plane. No other form of helicopter shows any promise of attaining negative $\delta M/\delta u$ over the whole speed range. Usually an unstable region exists at low speed.

Stick fixed stability is achieved by positive dihedral (or variable dihedral becoming positive in the upper range of forward speed). This stability is illustrated in Fig. 6 giving the position of controls over the speed range in level flight.

Dynamic stability has been investigated mainly in hovering. It is well known today that dynamic instability in hovering is mainly caused by the existence of a moment derivative with regard to horizontal translational motion. In a three rotor machine having a (virtual) negative dihedral, this derivative can be suppressed and even changes sign. Under such conditions dynamic stability is obtained as shown in Fig. 7 representing graphs of the stability parameters over the dihedral angle. The graphs refer to longitudinal motion but apply to lateral motion as well. I am indebted for these graphs to DR. SISSINGH who very kindly confirmed and improved upon our own calculations.

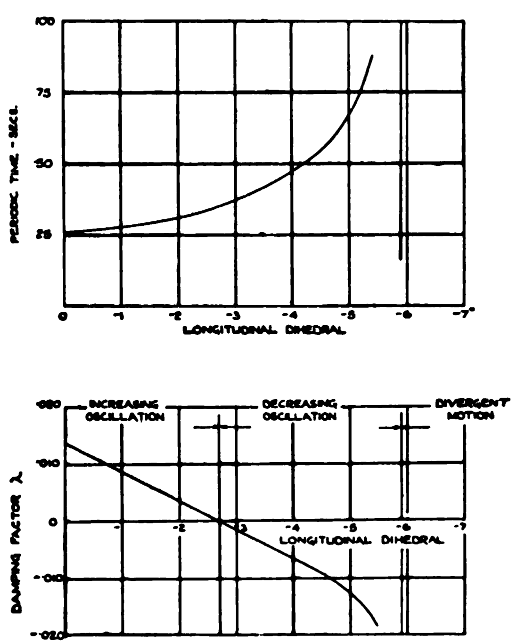


FIG. 7.—Longitudinal stability in hovering flight at sea-level. (C.G. position 59 per cent. aft of front rotor).

Undercarriage. As a consequence of the geometry of the three rotor helicopter, it is possible to provide the undercarriage with relatively large track and wheel base without any weight penalty. The importance of this feature will be apparent when it is recalled that the majority of accidents to rotating wing aircraft in the past have been due to overturning on the ground and could have been avoided by increasing the track of the undercarriage.

In the " Air Horse " the legs are so spaced in relation to the radii of gyration of the machine that non-symmetrical landings are only slightly more severe than symmetrical landings.

Layout. The Lay-out of the machine provides unobstructed entry into the main load compartment. Further, on single rotor machines, the fore and aft limits of the centre of gravity are rigidly prescribed not so much from the point of view of static stability which is, in any case, problematical and depends mainly on the vertical position of C.G. but from the point of view of control range. In the " Air Horse," due to the extremely powerful pitching control, such a restriction does not apply in practice and no difficulty will be experienced in flying with the centre of gravity as far as two feet off the mean position in either direction. This fact greatly facilitates the loading procedure and is likely to be especially appreciated in freight carrying machines.

Due to the absence of a tail rotor and the elevation of the main rotors, the " Air Horse " is completely free from the usual hazards to personnel on the ground.

CRITICISMS.

Having enumerated some of the principal advantages of the three rotor configuration, we now have to turn to criticisms likely to be advanced against this form of helicopter and examine their justification. It is natural to question the complexity of a three rotor machine with its multiplication of blade articulations, transmission elements and controls. Furthermore it is expected that the weight penalty as well as the drag penalty of the outriggers and long travel undercarriage legs will have to be justified on performance grounds in spite of the numerous other advantages of the configuration.

No definite answer to such criticisms can be provided without first choosing a suitable criterion derived from a distinct approach to helicopter operation. It is my intention in this paper to underline the quantitative approach and to choose the point of view of the commercial operator selling the use of " helicopter communications." In this way, from the great number and variety of considerations applicable to the evaluation of a helicopter, those expressible in economic terms can be selected and correlated under the guidance of the over-riding aim " to provide helicopter transport services at low cost in terms of pence per ton mile or passenger mile at a speed leaving a substantial margin compared with ground transport and accompanied by the highest possible safety."

Once commercial operation is considered, the criticism of complication loses its significance as an independent yard-stick in evaluating the helicopter or any other piece of equipment. From this point of view, to be significant, complication must be expressible in terms of first cost and/or maintenance.

As regards first cost, it is believed that the multiplication of components carries with it the tendency to cheapen manufacture by increasing numbers. We are all aware of numerous examples in technical development where multiplication of components has no specific effect on first cost. I only need to mention multi-cylinder engines or ball-bearings.

As regards maintenance, final judgement will have to await practical experience, but it is believed that the advantage of accessibility obtainable

in a three rotor machine of the size of the " Air Horse " and the reduction in the relative cost of spares through interchangeability, outweigh the disadvantages of multiplication.

We are left, therefore, with the problem of evaluating the "Air Horse" from the point of view of performance expressed in terms of transport economics. The evaluation will be divided into two main chapters dealing with the relatively independent features; three rotor configuration and long travel undercarriage.

Economics of the Three Rotor Configuration.

We formulate our first problem in the following terms : are the advantages of the three rotor helicopter accompanied by a weight and drag penalty leading to increased cost of helicopter transport ?

We are mainly concerned with examining the three rotor configuration in comparison with others. However, it is essential to ensure that other things are equal. Among other things we include the remaining principal factors determining the economics of helicopters, that is : Size ; Choice of parameters, and Detail design.

It will at once be obvious that we cannot replace a theoretical evaluation, however uncertain and based on inspired guessing, by a direct comparison of existing types simply because no such types are available of equal size, equal approach to optimum parameters, or equal stage of design development.

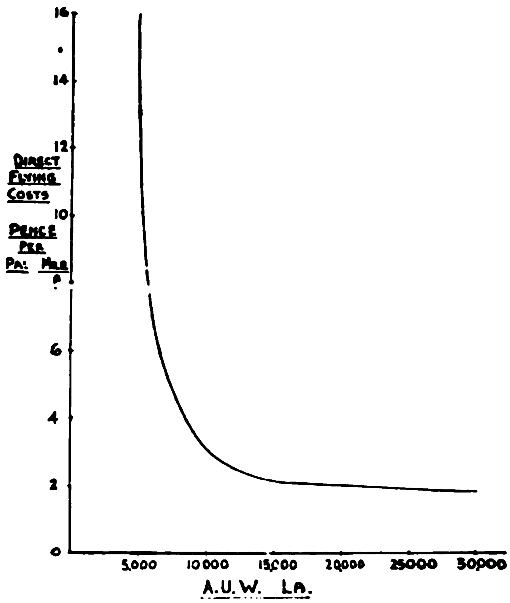


Fig. 8.

Direct flying cost *v.* A.U.W.
Passenger carrying helicopters.
Stage length = 100 miles approx.
Load factor = 100 per cent.
Utilisation = 2,400 hrs./year.

Referring to the chosen criterion of economic efficiency, we can narrow it down by first examining the conditions of safety and speed. Some of the advantages of the three rotor configuration enumerated above are concerned with safety. In addition it is thought likely that, except for special duties, the twin engined version will be the only one employed for civil transport.

All helicopters under development today are inherently capable of substantially identical cruising speeds of about 115 m.p.h. and the " Air Horse " promises to attain this speed with economical cruising power.

Consequently that speed can be eliminated as a factor in comparing the economic efficiency of helicopters, and we are left, therefore, with a cost comparison alone.

Effect of Size. Fig. 8 illustrates the fact that up to the size of the " Air Horse " and beyond, the effect of size on cost is predominant. This graph is based on existing helicopters, but includes the twin-engined " Air Horse." Fig. 9 applied to three rotor machines only shows that size has a far less pronounced effect on the percentage of disposable load. Such a

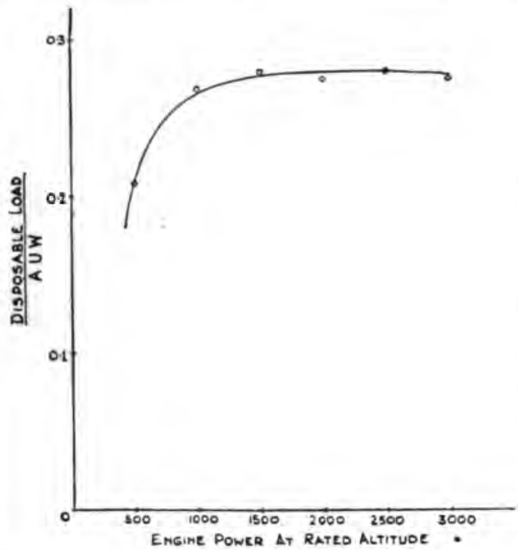


FIG. 9.

Disposal load/A.U.W.
v. Power at rated altitude.
3 rotor helicopter, tapered, twisted blades tip speed = 550 ft./sec.
Optimum disc loading.
Minimum solidity.
Minimun U/c. travel.

conclusion is roughly in accord with fixed wing experience in the range of sizes considered here and represents the balance of several opposing tendencies. The effect of size on the cost of transport is due to cost items, such as crew remuneration, which are predominant in small sizes.

Effect of Configuration. It is most profitable to restrict our approach and to compare multi-rotor helicopters having different numbers of rotors. In this limited field, at least, the comparison expresses real trends. Such an evaluation extends to all out-rigger machines from side by side twin rotors to three and four rotor configurations. It is based on the assumed laws by which weights of different components alter with basic physical magnitudes of the helicopter to which we shall return later. Fig. 10 shows that a very considerable improvement results from increasing the number of rotors from two to three. Further possible improvement is limited and may no longer justify the additional complication.

This graph cannot, of course, cover single rotor, tandem, intermeshed,

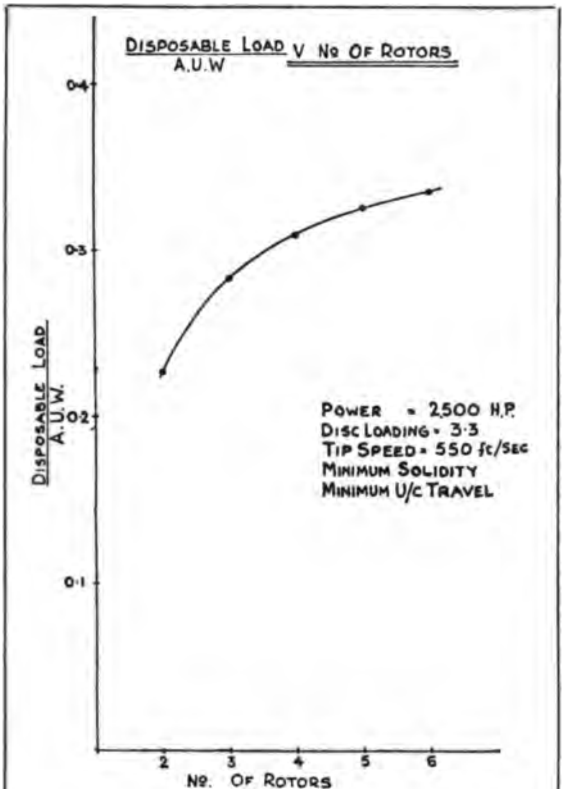


FIG. 10

or co-axial configurations which are the present practical competitors of outrigger lay-outs. In each case, if we take the side by side outrigger system as a basis, there will be items causing weight reduction as well as items causing weight increase. My point is that the best alternative system which I personally believe to be the tandem machine, is only marginally better than the side by side twin and therefore probably inferior to the three rotor machine.

Other performance aspects are more easily dealt with. It can be stated with some assurance that the gliding angle of the three rotor machine as a whole is of the same order as that of the better single rotor machines. This is due partly to the utilisation of the rear outrigger booms to produce lift in forward flight and partly to the effect of size.

Effect of Design Parameters. I cannot here deal with the subject exhaustively but, in outline, our approach consists of the following steps, each one containing somewhat bold and debatable assumptions, but which in combination are plausible and consistent.

(1) Definition of permissible All Up Weight.

(2) Determination of truly independent parameters.

(3) Subdivision of component weights into groups depending on individual parameters and their combinations.

Briefly All Up Weight is limited to that which can be lifted vertically at a rate of 6 ft./sec. by maximum engine power without wind or ground interference under the worst atmospheric condition in which the machine is expected to operate. To avoid a " multiplication of pessimisms " average individual efficiencies are chosen and a total allowance of 4% power loss is made to cover all errors.

There are four major design parameters once the configuration is settled and the power unit chosen :

(*a*) Disc loading. (*c*) Bladė solidity.
(*b*) Tip speed. (*d*) Undercarriage stroke.

Of these (*c*) and (*d*) prove on investigation to be dependent upon others.

Fig. 11 illustrates the effect of disc loading on the percentage of disposable load for a given power. It is seen that the effect of disc loading flattens out and remains stationary over a considerable region. Disc loadings of the two Air Horse types are near the maximum. I would like to make it clear that these graphs represent a comprehensive approach. In all cases, for instance, solidity is automatically adjusted to avoid tip stall and U/C stroke is automatically increased to absorb the energy of unaided vertical descent without power.

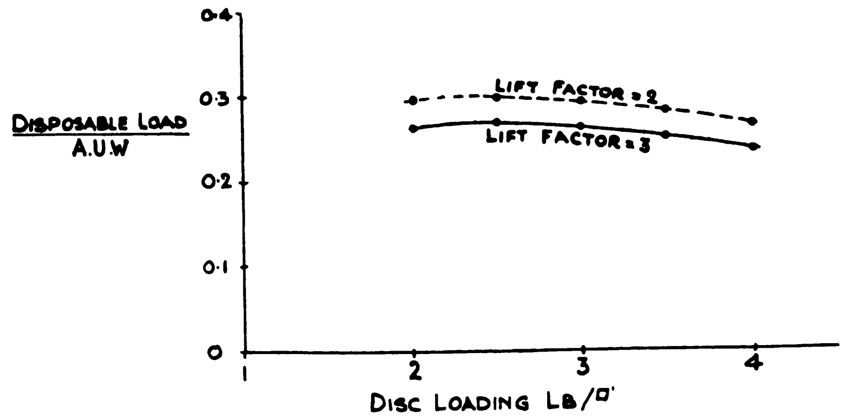


FIG. 11.—Variation of $\frac{\text{DISP. LOAD}}{\text{A.U.W.}}$ with Disc loading
Engine Power : 1000 H.P. Top speed 500 ft./sec.
Minimun solidity. Minimum U/c Travel.

In contrast to disc loading graphs, those showing the percentage of disposable load over the representative tip speed (Fig. 12) have no optimum. We have to re-emphasize that rotor solidity is adjusted for each tip speed to a value determined by tip stall in forward flight.

The Figure includes a graph of the kinetic energy of the rotors. It is seen that the effect of decreasing solidity nearly offsets that of increasing tip speed and the kinetic energy increases very slightly with increasing tip speed.

Effect of Detail Design. A novel configuration presents new problems requiring time and experience for their solution. It calls for caution but it also offers new opportunities to the designer. In particular, larger size contributes to the possibility of greater refinement and the lay-out of the " Air Horse " facilitates attention to ease of maintenance. The three-fold repetition of many components makes every improvement in the design of such components *three times* more effective.

Summarizing, we can conclude that the " Air Horse " constitutes a most important advance in economic efficiency on account of its size made

possible by multiplication of rotors, that the three rotor configuration compares favourably with the best known alternatives and its numerous advantages are not bought at a sacrifice in economics, that the " Air Horse " represents a choice of design parameters approaching the optimum in all but tip speed, and that, for its potentialities to be fully applied in detail design, type development will be pursued promising to reach really high standards in the twin-engined version.

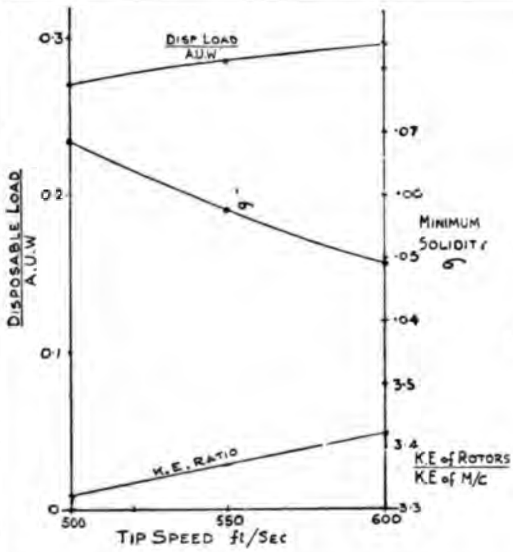


FIG. 12.
The effect of tip speed.
Power = 2,500 h.p.
Disc loading = 3.3
Minimum U/c. travel.

ECONOMICS OF THE LONG TRAVEL UNDERCARRIAGE.

The " Air Horse " undercarriage has a travel of five feet which enables the machine to carry out an emergency landing in vertical descent without power and without relying on the kinetic energy of the rotors. The rate of vertical descent is estimated at 41 feet per second and the energy absorption is, therefore, approximately 12 times that corresponding to minimum ARB requirements.

In providing a high absorption undercarriage the Company were guided by the following considerations :—

(*a*) That safety features independent of the pilot's skill are likely to be far more effective than those depending on a rather precise manoeuvre requiring great presence of mind and experienced judgement.

(*b*) That loss of power is experienced often immediately after take off when there is no time for the pilot to carry out the required landing manoeuvre. In fact, to reduce, if not escape, the danger at small heights over the ground, it is necessary to follow a take off and landing technique which, apart from using maximum r.p.m., includes inclined climb as well as taking account of the prevailing wind. Such procedures militate against the main advantage of the helicopter, namely all weather operation from strictly confined spaces. It is visualised that the helicopter, to do justice to its

principal function and to simplify landing facilities and navigation, has to be able to take off and land truly vertically and to be independent of wind direction. These considerations apply more particularly under conditions of poor or zero visibility. Imagine the advantage of knowing that you can hit the deck at a vertical rate of 20 m.p.h. without the slightest inconvenience!

(*c*) To substitute effectively kinetic energy for undercarriage absorption capacity it is necessary to provide enough of it at take off and landing.

A full analysis of energy transformation in vertical descent is complicated, but for the purposes of our argument, it is enough to state that in *practice* (that is allowing for a normal degree of error on the part of the pilot) the available kinetic energy in the rotor must be a multiple of the kinetic energy of the machine in vertical descent. Some published data lead to the conclusion that the factor ought to be about 5 for adequate safety.

Referring again to Fig. 12 we observe that without special attention to this matter we may expect, in a well designed three rotor machine, a factor of 3 varying only little with tip speed.

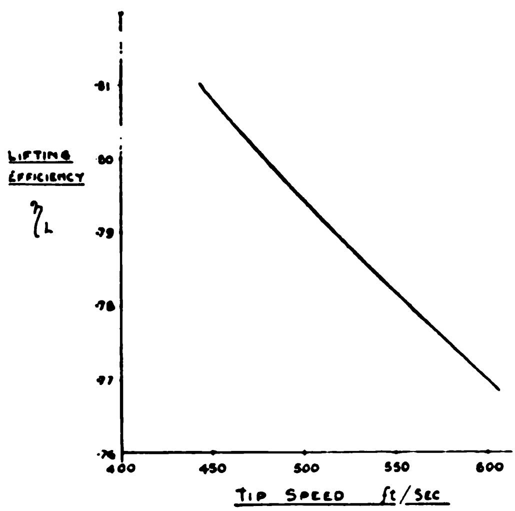


FIG. 13.

Lifting efficiency *v.* tip speed tapered twisted blade.

Disc loading = 3.5lb./sq.ft.

Normal solidity = 0.05.

To obtain the missing 66% of available energy we can either increase tip speed by 30% *keeping the same blades* or increase blade inertia by 66% with constant tip speed. The former procedure will reduce the lifting efficiency by as much as 4% as can be seen from Fig. 13 giving lifting efficiency over tip speed at constant solidity. The latter solution will add 4% to the structural weight.

On the other hand, the weight sacrifice for long travel amounts to barely 3% of All Up Weight which is less than the useful weight increase obtained by enabling the machine to take off, hover and land at optimum blade angle.

OPERATORS' REQUIREMENTS.

Though this contribution to the discussion was broadly intended to represent the constructor's reply to requests expressed earlier by operators,

we have until now concentrated on the description and evaluation of a type already in existence. We can now turn to the operator's problems but will have to restrict ourselves to brief remarks.

We have to classify requests made by operators into several categories.

(*a*) Many of the features which distinguish the " Air Horse " either inherently or incidentally, directly meet some of the points raised by the lecturers and have, in fact, been introduced in response to such requests.

(*b*) To be honest, every designer has to admit that many troubles experienced by operators arise not from inherent difficulties but merely from lack of foresight. No purpose is served by covering up lack of attention, and the remedy for such faults lies in better appreciation of the problems by the operators themselves, and better co-operation between operators and designers. This discussion must be especially welcomed from this aspect. Specifically, it cannot be denied that in helicopters some, though not all, vibration troubles fall into this category especially those arising from avoidable unbalance and resonant response to periodic impulses which, in themselves, are not intolerable.

(*c*) Operators must realise that some of the requirements put forward by them are conflicting. Most improvements have to be paid for with money or weight, or both. To do justice to such conflicting requirements it is essential for the designer to be given some guidance of a quantitative nature as to the relative value of the different requirements. It is admitted that such information may be extremely crude at this early stage of practical experience. My point is that crude information is better than none.

(*d*) Finally, there are requirements to which the designer is fully alive but which constitute real technical problems requiring systematic research and development, for their solution.

Progress will be determined by the effort invested in research and we all hope such research will receive assistance and sponsorship on a scale commensurate with the promise of the great benefits which the public expects from further developments of helicopters.

POTENTIALITIES OF THE " AIR HORSE " IN CIVIL AIR TRANSPORT.

The present achievement is characterized by a percentage of disposable load of 32% in the freighter version corresponding to 27% in the passenger version. Although this figure may drop somewhat owing to additional operational equipment, we recall that it approaches the figure of 28% given for the " Ambassador " which is a highly developed, conventional, fixed wing aircraft. It cannot be stressed too strongly that such an achievement in a completely novel configuration means that the potentialities of the type are very much greater. The policy of our Company is to pursue development along the line of increased all-up-weight with the twin-engine installation, preserving many of the existing components. Experience with the " Air Horse " research prototype will enable us to depart from the caution with which such a novel conception had to be approached. It is confidently expected that the twin-engined " Air Horse " will have a disposable load percentage of 30% in the passenger version and 35% in the freighter version, with full operating equipment of approximately 800 lb.

Present estimates of direct cost for the twin-engined " Air Horse " are of the order of 1.9 pence per passenger mile for 100% load factor, and a stage length of 100 miles.

The load factor in helicopter transport must be considered without prejudice from fixed wing experience. It will be greatly influenced by tariff policy and by the frequency of the service and must at present remain highly speculative. However, even if we assume a load factor of 65% the direct cost per passenger mile becomes 2.66 pence.

All that can be said at present about overhead expenses is that they must be inherently lower than those of fixed wing aircraft due to the basic features of the helicopter which requires only a fraction of the ground installations and facilities essential for fixed wing operation. I believe that overhead expenses of 33% are a generous allowance which can eventually be reduced to 25% or even 20%. We thus arrive at an economical fare of less than 3.5 pence per passenger mile. I visualize the single fare between London and Birmingham to be 28/- compared with the present single first-class rail fare of 37/9. On the basis of a cruising speed of 116 m.p.h. the scheduled block time of the journey would be 59 minutes. Similarly, a single fare between the centre of London and the centre of Paris would be exactly £3 and the journey would take two hours and two minutes.

Few people would disagree with me in expecting that if these figures can be obtained, and I believe them to be quite within our grasp in three to four years, a vast volume of traffic will be carried by helicopter services over routes such as those mentioned above and I am confidently looking forward to the day when from a helicopter station in the centre of London, twin engined " Air Horses " will rise every 20 minutes and carry 30 passengers to Paris, or Brussels, or Birmingham, or Manchester.

ACKNOWLEDGMENTS.

Whilst other contributors to this discussion share the distinction of leading the design teams responsible for their machines, I was merely given the honour of representing the team of the Cierva Autogiro Co., I have to pay very special tribute to the pioneer of successful helicopter flight in the United Kingdom, our Chief Designer and Managing Director, MR. C. G. PULLIN, and my colleagues, the Deputy Chief Designer, MR. H. BOLAS, the Chief Mechanical Engineer, MR. K. WATSON, and the Chief Test Pilot, MR. H. A. MARSH, as well as to the able and devoted staff of the Company who have made the design and construction of the " Air Horse " possible.

When the achievement of the " Air Horse " is judged as the latest link in an unbroken line of development, the Rotary Aircraft World owes a great debt to our President, MR. J. G. WEIR, for his pioneering devotion for the last twenty-five years.

The continued sponsorship given by the Ministry of Supply to our work deserves the profound gratitude of all rotating wing enthusiasts and we all know to what degree this sponsorship has been inspired by and personified in Captain R. N. LIPTROT, Director of Research and Development.

Finally, let me express our thanks to all our friends, whether at the R.A.E., Farnborough, or among our Suppliers and Sub-contractors, who, by showing their enthusiasm and doing a little more than priority justified or duty demanded, made this achievement possible at a difficult time.

Discussion.

A. Davenport (Westland Aircraft Ltd.) *Founder Member* : The request which had been made during the morning session for more money with which to develop the helicopter was not unusual ; and the reason given, that the helicopter industry was not getting its share, was also not an unusual complaint. But some encouragement might be derived from the consideration that those who were concerned to buy helicopters would not always require that they be operated economically or at a profit. Sometimes a service was run at a loss in order to serve the convenience of the customers ; and probably the helicopter would render the sort of service that could be run at a loss, or without profit, provided that the whole organisation of which it formed a part was run at a profit.

Mr. Peter Masefield, in his recent lecture, had suggested that the helicopter was not able to make journeys of more than 200 miles economically ; at that stage the fixed-wing aircraft came into its own.

The installed power per passenger was rather low for it worked out at about 75 h.p. per passenger in the helicopter, whereas in its fixed-wing competitor it averaged 50 h.p. per passenger. That matter required attention, and improvement might well be effected by improved design and construction of rotor blades.

He disagreed with Captain Liptrot that replacements were excessive in the helicopter ; in his experience with the Sikorsky S.51 there was a major inspection at 400 hours, and the cost of replacements was less than £100. That was a remarkable achievement, because that particular machine had been doing demonstrations and intensive flying.

Another matter in connection with operation costs was that of the consumption of fuel, which for the helicopter worked out at 3½ m.p.g., whereas in the fixed wing it averaged 7 m.p.g. Thus, there was much room for improvement, and he suggested that designers of helicopters might pay a little more attention to streamlining, particularly if the machines were to cruise at more than 100 m.p.h.

He supported Mr. Scott-Hall that designers should pay adequate attention to improving the stability of helicopters so as to make blind flying, map reading, and general navigation easier in adverse weather and other conditions. He also thought that the noise level in the helicopter at present was too high and should be improved, from the engine transmission, blades, and engine exhaust.

Norman Hill, *Founder Member* : He was a would-be operator of British helicopters. One speaker had stated that there was no market for the helicopter, or if there were, that it was small. He suggested that if they concentrated on producing a marketable helicopter the market would then become apparent.

Under present-day conditions development and production was a slow and tedious business for the manufacturers, and even to-day there was no British helicopter available with a full certificate of airworthiness. Furthermore, the experimental prototypes demonstrated so far had only a moderate performance and a poor capacity.

The insurance underwriters, suspicious of the helicopter and its mechanical complexities, and lacking experience and knowledge of the type, quoted rates for insurance which could only be described as harsh.

At State airfields landing fees were heavily against the type, although the wear and tear at such airfields caused by the helicopter was negligible when compared with fixed-wing aircraft. All these things weighing so unduly against it might prevent the helicopter, with its unique capabilities, from being properly exploited.

He should suggest that designers and engineers engaged in the British effort should *seal* their designs immediately practicability in performance and cost was apparent, and then let the operators who had the vision, the enterprise and the money, put the helicopter to the proper operational testing it required, if it were to secure its rightful place in commercial air transport.

Those interested in insurance underwriting should make themselves familiar with the helicopter and all its possibilities. This promising aircraft should not be burdened with heavy insurance rates without regard to its safety characteristics—characteristics which were clearly to be seen when in the hands of airline operators with an appropriate technical and financial background.

To those who were to-day framing legislation for the helicopter he would say—have safety by all means as their code, but frame and apply regulations with wisdom and vision so as not to hamper this new vehicle in its free development.

G. A. Ford (B.E.A. Helicopter Unit) *Founder Member :* As a pilot in B.E.A., he would definitely like to see some form of manual over-ride control with which the pilot could cushion a vertical landing in a restricted area, and also increase the pitch to compensate for the lower air density and the loss of engine power with height.

The fixed-wing aircraft instrument panel layout was the result of a number of years practical experience, and the principles that governed that layout should be applied to the helicopter. In particular the blind flying instruments should be in front of the pilot and close together, even at the sacrifice of a little of the forward view. Any improvement in stability would be a great asset to a pilot flying blind or by night.

H. Roberts (Department of Aeronautics, Imperial College of Science and Technology,) *Founder Member :* There was a certain degree of over-optimism perhaps to be found in the Lecturer's approach to the problems of rotary wing aircraft. There were three main stages of development in any problem ; investigation of the effect, the cause and the cure. The Lecturer's had said a lot about the causes of helicopter problems, *e.g.*, the problems of stability and vibration, and the effects were fairly widely known. Thus excessive vibration led to discomfort during flight and fatigue failure of parts, while inadequate stability involved a higher degree of risk, and consequently reduced safety. What seemed to be lacking was that the Lecturers—particularly on the question of stability—had said little about the application of present-day ideas to provide improved answers to the problems.

The particular problem of vibration seemed to be getting the attention it deserved, and he congratulated the designers on their various ways of alleviating vibration troubles. But the " solution " to the stability problem offered by Mr. SHAPIRO was far from new, having been handed down by the earliest pioneers. Dr. BENNETT's solution, involving the use of a fixed tailplane gave stability only at forward speed, and was merely an adaptation of fixed-wing concepts. The Bristol machine apparently could only be stable over a limited range of forward speed. It seemed that all these so-called solutions were not really genuine solutions in the sense that they enabled them to achieve stability over the whole speed range without extreme complication or difficulty.

During the discussion it had been said that stability would be provided when it was required by the customer. He did not know whether or not it was proposed to provide it from a hat, like the proverbial rabbit, but stability would certainly not be provided just like that. Its achievement called for really hard work by a lot of people. In Great Britain there were a certain number of experts, but nothing like the number that the situation required. In contrast to their own limited resources, in the United States there was intense activity by a large number of design and research organisations and it was probable that advances there could be more substantial than in this country ; he could not help feeling that they were likely to be behind for a long while.

One of the roots of the trouble was that the teaching facilities in Great Britain for training engineers in this field were far too limited. The new syllabuses of the " Aircraft Design " paper for the Associate Fellowship Examination the Royal Aeronautical Society, for the first time, was proposing to include specifically the rotary wing aircraft. He hoped that this, together with the activities of the Helicopter Association, might provide a fillip to the teaching organisations to extend their activities and facilities in this direction, so that eventually they might produce that body of designers and research engineers needed.

Whereas Mr. FITZWILLIAMS had said that the function of the helicopter was to deal with the low speed end of the speed-range, Dr. BENNETT had said that his machine was designed, not so much for the low speed end, but for a high cruising speed. Perhaps they might be able to resolve that slight inconsistency.

Mr. TYE had said that he did not know of a solution of the general layout problem which gave reasonable fuselage shapes. If a fine fuselage were required there would be no difficulty in providing it. But the solution which looked best, so far as aerodynamic lines were concerned, was not necessarily the best solution for the overall aerodynamic performance. The morning discussion seemed to exaggerate one side of the picture.

In Mr. HAFNER's first graph he had very high values of μ. The symbol μ did not generally exceed 0.5 or 0.6 and he would like to know what was meant by values of μ of 1, 2, 3 and 4.

In Mr. HAFNER's equations there appeared a term which allowed for the deflection of the induced flow as it approached the disc, so that the effective angle of attack of the

disc was altered. He was under the impression that deflections of this sort were not substantiated experimentally and there was a fair amount of argument— and it was very much a matter of opinion—as to whether there was any justification for using the deflection angle on a parameter.

Stability had been recommended in forward flight, but not necessarily in hovering flight. It seemed to him that the problem of achieving stability in forward flight was not difficult, and he did not think that anyone had said that it was. The difficulty was to achieve it in hovering flight, and he felt that it was rather begging the question to suggest that people really did not want it.

Pierre Renoux (S.N.C.A.S.E., Paris) : A flying model had been made of a family of new helicopters developed by the S.N.C.A.S.E. which included some unorthodox features. A picture of it had been published. It had two tail rotors, which had advantages in connection with the control of the pitching and yawing components, and very good damping in pitching and yawing motion was secured.*

G. E. Clair (Aviation Underwriter, The London and Lancashire Insurance Co. Ltd.) : He welcomed the remarks of Mr. NORMAN HILL on insurance and noted that Mr. HILL hoped underwriters would enquire more closely into the helicopter situation. That request, to some extent, had already been met by the presence of two insurance representatives and much of value had already been learnt.

If underwriters could have information as to the possibilities of autorotation in the event of engine failure, the loss of height necessarily involved and the heights at which any such failure could be handled safely it would be helpful. For example, he had gathered from Mr. HAFNER's remarks that there was a possibility of landing the Bristol 171 with only a 50 yards landing run which seemed quite good.

Mr. HILL had referred to harsh rates ; he assured him that in the present competitive state of the market, underwriters did not charge more than they could help. Harsh rates were the result of bitter experience during the past few years, mainly on the Continent of North America, and some underwriters to-day even refused to look at the business. But whatever proposition was put forward, provided that the safety factors mentioned were clearly brought out, it would be found that the insurance market, instead of being rather nervous, would do all that was possible to help, by covering the new and interesting development in aviation.

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* Mons. Renoux had brought a cinematograph film showing the operation of the model, which he was asked to leave with the Royal Aeronautical Society so that it could be shown at a later date.

THE CHAIRMAN.

This afternoon we have had but a very short time available for discussion. The meeting will now adjourn for tea, but at 5 o'clock we shall again meet and continue the discussion both of this morning's and this afternoon's papers and the problems that arise from them.

I would like to point out that if there is anybody here who has wished to take part in the discussion and will be unable to be present this evening, if they will submit their comments in writing to the Secretary of the Royal Aeronautical Society these will be answered by the Lecturers and will be included in the published discussion.

EVENING SESSION

General Discussion.

DR. H. ROXBEE COX, D.I.C. F.R.Ae.S., F.I.Ae.S.

President of the Royal Aeronautical Society

in the Chair

J. K. Williams (Air Registration Board) *Member* : He emphasised Mr. CLAIR's point which was not fully appreciated by everybody, about the introduction of safety factors in order to reduce insurance rates.

The helicopter had definitely arrived as a successful flying machine, but the eventual helicopter passenger, the "man-in-the-street," still regarded the helicopter as a spectacular piece of ingenuity, capable of performing incredible tricks in the air, but not yet as a means of transport. In the next few years helicopter designers must concentrate on safety and on improving the efficiency of the design with regard to the percentage payload available, instead of increasing the complexity of the design in order to achieve spectacular records. He did not wish to belittle the splendid accomplishment of the Fairey Gyrodyne in attaining the speed record, but he felt sure that Dr. BENNETT would be the first to admit that the attainment of that record was only incidental to the completion of a successful design.

From the safety point of view there were five major problems to be studied and overcome. They were :—

1. The helicopter at present was far too complex with too many moving parts. Simplification was needed to reduce the risk of failure of a component part which might be vital to the whole. They must make certain, by means of additional safety factors and check laboratory tests, that within the specified life, the parts, including gears, bearings and rotor blades, remained airworthy.

2. They had little knowledge of the loads which helicopters actually experienced during manoeuvres in flight. The various types should be extensively flight tested with strain gauges to obtain a more accurate estimate of criteria for design purposes so that, not only could they be reasonably assured that the helicopter was safe for normal manoeuvres, but also that the structure was as efficient as possible, without introducing undue failure hazards.

   One of the most important problems was the possibility of the fatigue failure of a main rotor blade in flight. A great deal of reasearch was necessary to establish adequate design safety factors and the technique of the laboratory fatigue tests. An excellent treatise on that subject had been written by Mr. GARRAWAY in his Cierva Memorial Prize Essay.

3. The single-engined helicopter was a far safer flying machine than a single-engined aeroplane in the event of engine failure but, as Captain LIPTROT had pointed out, a danger zone, for engine failure for single-engined helicopters did exist. It could be eliminated by making the helicopter twin or multi-engined, or so designing the rotors that the pilot could use their kinetic energy to reduce the vertical velocity (before touch-down), or by the provision of a long travel undercarriage.

   He agreed with Wing Commander BRIE that all future helicopters in operation on scheduled routes should be twin or multi-engined types, the basic performance requirement being that the helicopter could maintain height on one engine under adverse conditions.

4 A reduction in the disc loading was needed. There they were faced with the paradoxical problem of reducing the disc loading and at the same time increasing the percentage payload to make the helicopter a competitive means of transport.

5. A successful technique for the complete blind flying of helicopters must be devised, with the attendant problems of the development of instruments and ground aids, reduction of pilot fatigue to the minimum, and overcoming the inherent instability of helicopters in their present stage of development. He believed that the B.E.A. Helicopter Unit would solve that problem successfully before long.

If these safety aspects could be successfully incorporated during the next few years, what were the future fields of operation for the helicopter? The whole trend of development depended on that. Surely thay would not be satisfied with the limited fields envisaged at the moment, such as crop-dusting and spraying, Post Office work and shuttle services between the Scottish islands. Could they look forward to helicopters superseding fixed-wing aircraft on some of the major internal airlines in this country during the next ten years or so? If not, he felt that helicopter development would be seriously retarded.

Dr. A. P. Thurston *Member*: What was the correct pronunciation for the machines under discussion; he had heard them called "helicopters," "heelicopters," "haylicopters," and Group Captain LIPTROT had even called them "witches cauldrons of fluctuating forces"; years ago Sir HIRAM MAXIM had called them "hell-icopters."

He sympathised with those who complained that money was not available for the development of this most important branch of aeronautics, but much development could be effected at little cost by means of models. For many years he had experimented with models, some of which did not conform at all with practice, and it seemed to him that with them many problems would be solved concerning the fluctuating forces which set up vibrations, and so on. He exhibited one of his models, which was stabilised like an ordinary aeroplane; it was dated 1939. It flew best when *not* pivoted at the root of the blade and he showed the optimum point of pivot. At times he had been in peril, by reason of the speed of the models in the air, which was unbelievable. Such blades spaced themselves when flown in multiple. He had used all types and shapes of blades *stabilised* and had determined by experiment the best point to pivot the blade. Models could be controlled remotely by means of a Bowden cable with a centre wire; differential control, pitch control and any other form of control of blade or engine could thereby be achieved.

A. H. Yates (College of Aeronautics) *Member*: What was being done to narrow the range of danger heights between which, if engine failure occurred in a single-engined helicopter, a crash appeared to be inevitable? If an engine failed at a height below 30 ft. the landing could be cushioned by increasing the blade pitch. If an engine failed at a height above 300 ft. there was sufficient height for the auto-rotation of the rotor to be achieved but at less than 300 ft. there was not that opportunity. It was desirable that, as soon as torque failed, the blades automatically set themselves to autorotating pitch, without time lag.

The pilot of a fixed-wing aircraft had to be on the extreme *qui vive* for only a few seconds after take-off, and had not to watch the controls so carefully when a comfortable height was achieved, but the helicopter pilot had always to be alert and was at a disadvantage in that respect.

Helicopter meetings seemed to attract people of such diverse interests that he wondered if the time had come when the specialists should separate. There were references to laminar flow, the Fourier series, and so on, and these subjects would not interest the "crop sprayers." Those interested in aerodynamics could very well spend the whole day discussing the aero-dynamic features of the aircraft, and they might gain, perhaps if the meetings were a little more specialised.

F/Lt. J. R. Anderson, *Member*: At a joint meeting of both rotary-wing and fixed-wing experts, it seemed appropriate to mention the combination of the two types of aircraft. So far the only reference to the type had been a mention of convertible aircraft by Mr. FITZWILLIAMS. The combination was now a practical proposition because of developments in gas turbines and in other technical spheres.

With convertible aircraft the landing and take-off difficulties of the fixed-wing aircraft could be overcome to a great extent and, for a given engine power, the convertible could show less than half the drag area, which meant higher speed. For heights below 8,000 feet, it meant that the convertible type could be operated at speeds which fixed-wing aircraft could not touch, and thus could fill the gap between the helicopter at the lower heights and the fixed-wing aircraft at high altitudes.

There were none of the vibration difficulties found in the helicopter because of the periodic forces on the blades, since the axes of the various airscrew systems were not at approximately right angles to the air flow.

They lagged behind with helicopters through insufficient support, and one speaker had suggested this was because of their low military value. The convertible type had high military potentialities and its development was of importance—possibly vital—to the defence of the country. It was to be hoped that those responsible would not bury their heads in the sands of complacency. The papers presented to the meeting had clearly explained the limitations of the helicopter, and he hoped that support, both financial and in other directions, would be forthcoming from the departments concerned.

Wing Commander L. P. Gibson *Member*: It had been said that fixed-wing aircraft pilots with thousands of hours of flying had " given up the ghost " after trying to fly the helicopter and that, in trying to fly the helicopter, it was as though one were trying to balance a billiard ball on a pin. He felt that this was a slight exaggeration and the view that helicopters were difficult to fly had arisen largely, perhaps, because of the attitude of those who could fly them already ; they formed something like a " magic circle " or " closed shop." It reminded him of the old flying boat days and their " Union." There were two cases recently in which pilots had learned to fly the helicopter after only 1½ hours dual.

The lack of real facilities for learning to fly helicopters in Great Britain was perhaps the difficulty at the moment. People came along for a ride and their first flight was just a novelty ; they did not really learn anything from this.

He suggested that there should be established somewhere in this country a familiarisation course—not a course which would cost something like £300, but one which would include, say, five hours flying. He recalled that when jets were introduced there was established in the Service a week's course, which included five hours flying ; the whole idea being to dispel the " black magic " which had then surrounded the jet.

If helicopters were to be developed so that everybody could use them and could take-off from, and land in, their gardens, they must rid themselves of that " black magic " idea. The difficulties of flying the helicopter must not be exaggerated.

Squadron-Leader F. J. Cable (Airborne Forces Experimental Establishment) *Founder Member* : A middle course should be adopted on the flying of helicopters. They should not suggest that only a race of supermen could fly them and we must not go to the other extreme and say that they were easy to fly.

As to the stage at which a pilot should first be allowed to fly solo, it was one thing to get into a machine and fly it around the aerodrome, when everything was working well, and put it back on to the ground without damage, but it was another matter to operate and look after it regularly and to meet the cost of repairing the damage.

Difficulties, or the idea that the flying of helicopters was difficult, had arisen in the early days largely because of the mental approach and the necessity to appreciate the co-ordination of the controls.

There was no difficulty about the engine-off landing problem and that bubble should be exploded. At A.F.E.E., Beaulieu, they had made 500 or so engine-off landings successfully from various heights during the past few months. The Sikorsky R4 was in the nature of being an experimental machine. Tests had been made with it, with more or less success, and presumably test results with later machines would be better than those obtained with the R4. When operating the R4 at 2,700 lb. (the full weight was 2,800 lb.) in still air conditions they had cleared a 100 ft. screen and had come to rest within 125 yards. That was not a stunt, but had been done often ; he had been responsible for more than a hundred of those landings. To those who were interested from the insurance point of view, he could say that helicopters could be landed in one piece, depending largely, of course, on the circumstances and the skill of the pilots.

The helicopter could not be used fully until blind flying was a practical proposition. At the moment it was possible, but he would not like to say that it was practicable. In his opinion the first requirement before blind flying could be made practicable was stability. The helicopter was not free of troubles in that respect, but the problems were not insurmountable. Given a stable aircraft and the development of one or two instruments, blind flying would be practicable.

W. M. Evans (Air Registration Board) : Speakers so far had avoided mention of the power plant, but from recent discussions with helicopter designers it appeared that there was a feeling that a case could be made for a modified method of rating helicopter engines. The helicopter designers felt that they needed a power for hovering (which was say, 90 per cent. of the maximum power of the engine), a power higher than that for emergency conditions and there might be some third rating, such as a power limited by b.m.e.p. and r.p.m., at which weak mixture strengths could be safely used.

He had tried to obtain some collective idea, if such existed, as to how helicopters, particularly the new designs that were coming along, could be operated, and he had found it extremely difficult. It might be that, as with most new designs, the designers were more optimistic than other people, or alternatively, they feared their optimism. It seemed that, not only would helicopters take a far greater percentage of the maximum power of the engine for longer periods, in relation to the total period of flight, than would fixed-wing aircraft, but that the engine r.m.p. would tend to be narrowed down to within a tight band just below the maximum r.p.m. permissible for extended periods.

That meant that engines were going to have an exceedingly hard time in helicopters. Did the Lecturers think there was any possibility of the efficiency of the helicopter being improved to such an extent that it would no longer be necessary, a few years hence, to take these relatively large percentages of engine power from the engines ?

J. Brocard (Chief Engineer, Breguet Company, France) : He expressed his thanks for the invitation extended to the French engineers to attend the meeting, and the pleasure it afforded them to attend.

The first Bréguet helicopter had been built in 1905 ; in later years M. Breguet did further work in that field and in 1935 had secured the altitude record. Before the 1939–45 War a third machine had been built, which he believed was the only machine having two rotors, contra rotating, an arrangement which gave very good efficiency. The new machine was powered by a 240 h.p. motor and the diameter of the rotor was five metres (about 16 ft.).

Group Captain G. V. Howard *Companion* : He was interested in the use of helicopters for anti-pest spraying and dusting work and had made enquiries as long ago as December 1946 about insurance rates ; he was quoted variously 12 per cent., 10 per cent. and finally 7½ per cent. Because of the lack of helicopters from British sources, it had not been possible to proceed with the scheme at that time, but having been promised a Sikorsky S51 helicopter for delivery in February 1949, he had approached the insurance companies again in July 1948 and had learned to his horror that the rates had increased from 15 per cent. to 20 per cent. It was explained to him that the large increase was caused by the high incidence of accidents to crop spray and dusting helicopters in the United States. On making enquiries, he discovered that the accidents had occurred chiefly to tail rotors—not because of any mechanical defects in the rotor system, but on account of the rotors striking trees and hedges. His informant volunteered the information that the helicopter operators liked to get the chemical well into the corners of the fields and generally got as close as possible to the boundary obstacles before turning. In effect, the accidents were caused principally by careless or rash flying and he suggested that this factor should be made clear to the various British Underwriters interested in the insurance of helicopters engaged in crop culture.

Generally speakers had referred to the alleged difficulty of operating a helicopter and he would like to associate himself with the speaker who expressed the opinion that the pretence of some of the few original helicopter operators, to the effect that an exceptional type of person was required, was calculated to harm the helicopter industry and discourage would-be purchasers. He had been permitted to take a short course on helicopter operation and mechanism, at an R.A.F. Centre, while on his retirement leave and, judging by the description of a member of the staff concerning the complicated nature of operation, he formed the impression that at least four hands and two pairs of feet would be required. In actual fact, he found that while it was true that the technique required was very different from that of flying a fixed-wing aircraft, there was no great difficulty about it and he formed the impression that the average individual would qualify for solo flying more quickly than in the case of fixed-wing aircraft, because of the impossibility of flying slowly in the latter.

The creation of these mysteries by the experienced few was similar to the nonsense " Black Magic " of the earlier flying-boat pilots, who tried to make out that web

feet were required to fly a boat successfully. Every one now knew that the alleged difficulties were sheer invention and in actual fact the average landplane pilot experienced greater facility in operating a flying-boat, because of increased area for take-off and landing.

SUMMING-UP.

N. E. Rowe (British European Airways) *Member* : He thought of the " General Problems of the Helicopter for Civil Use " as being primarily passenger and freight carrying, although there were many other uses, a number of which had been mentioned.

They had tended to think all the time of a machine with a single main rotor, something which had the stability characteristics of the machine they knew, having the difficulties in connection with a single power unit and power cutting which characterised it. A good deal of the discussion was unduly coloured by their experience of the aeroplanes they had now, presumably because they had not experience of anything else, although there was a great deal of promise from the designers. A challenge had been made by the operator and the technical expert, and that challenge was answered by the designers ; in general he had concluded that many of the points brought out by the operator and technical expert were dealt with reasonably well by the designers. The designers' figures were still rather unrealistic in that they were not backed by full measurements or prolonged experience ; but on problems of stability and performance, engine-cut performance, and so on, it seemed that a good deal had been done, that those problems had been given real attention in design, and there seemed promise of getting what they wanted. In particular, Mr. SHAPIRO's claim that in his three-rotor machine he could attain stability over the whole speed range was extremely promising.

For civil use safe, reliable, economic operation was wanted. Safety, in the connotation of " civil use " which he had in mind, was perhaps best achieved by having multi-engines, a point made by Wing Commander BRIE, and he hoped they would get away from all the difficulties of engine cut and of landing with no power. Machines must fly perfectly well on part power, and that was one of the things expected from the designer.

In reliable operation were included all the points of maintenance, flying blind, good stability and control and operation in all sorts of weather. Group Capt. FENNESY had spoken of navigation, a matter which was of great importance in the whole set-up. If navigation could not be effected precisely and automatically, they were in great difficulty.

The problem of blind flying had not received the attention he had hoped. The meeting had tended to talk about stability and control rather that the actual practice of blind flying, although all agreed that it was necessary. In Great Britain it was essential for regular operation to be able to fly blind with complete precision of operation in terms of navigation, and complete safety in terms of control and stability and the pilot fatigue factor. Mr. FORD had mentioned the instrument layout, and the work that B.E.A. had done emphasised the importance of good lay out for blind flying, so that the fatigue, which was inherent in the helicopter to-day, was reduced to the minimum.

Wing Commander BRIE had made a very important point when he had urged that they must make the best use of what they knew already. Exactly the same sort of plea was made by Sir HENRY TIZARD in his Presidential Address to the British Association in 1948 ; he had said they would probably do more in advancing the general economics of life at this stage by making use of the knowledge they possessed now rather than by applying all their effort to the finding of new knowledge. He commended that point to designers and all others concerned.

The point made during the discussion concerning the provision of sites had not been taken up, although it was of great importance to operators. It was said that if they had the best helicopters, but had not the sites to and from which to operate them, they could do nothing. That was absolutely sound ; there was need for real drive in connection with the provision of sites, so that they could get them as economically as possible and in the best position for economic and convenient use. Another important point was that, since the helicopter was a short-stage vehicle, the number of sites in a given group system would be large, hence equipment, manning and so on of such places must be done on an economical scale.

There had been a fair amount of discussion on vibration. He had done a fair amount of riding in the S.51, and the B.E.A. pilots had done a tremendous amount of work. He would say that the vibration was rather high for comfort but not unduly

so. The point had been made by one of the designers that they should set down a standard of vibration which the operator would be prepared to accept; that was important because it would give the designers some idea of the limit on cruising speed imposed by passenger comfort. Vibration was important, but he had felt that there was a tendency to over-emphasise it.

He agreed on the point made that the total amount of effort being devoted to helicopter problems in Great Britain was too small and that they should have more training of technical men. More technical knowledge was needed but without training they would not get it.

Research with models was also important. There was a technique in connection with fixed-wing machines which used a sequence of calculations and model tests and correlation with full scale; he believed it was true to say that, correlation between model and full scale having been established, they could advance much more confidently into new territory than they could without the model technique. A similar technique was needed for helicopters. As things were now, they had to build a full-scale machine and find out what it was like. They should know a great deal more about it at the model stage; then they could advance with much more confidence and economy.

CONCLUSION

DR. H. ROXBEE COX (*Chairman*)

The Chairman said he had been particularly glad to see the French engineers and also to see so many who were interested in the insurance side of the helicopter business at the meeting. One of the diagrams in Wing Commander BRIE's paper was important from the insurance point of view; it showed how easy it was to walk into moving parts of a grounded helicopter, thereby damaging oneself and the helicopter, so that the insurance charge would be quite appreciable unless the greatest care were exercised.

One of Mr. SHAPIRO's diagrams, seemed to show that, if the number of rotors were increased on one of the multi-rotor machines, the ratio of disposable load to all-up weight tended to become asymptotic. That was puzzling. There was a clear difference between gaining further disc area by increasing the number of rotors and achieving the same result by increasing the area of each disc. It seemed to him that the former was more expensive in structure weight than the latter, and he would like to know why he appeared to be wrong on that point.

CONTRIBUTIONS.

B. H. Arkell (The Fairey Aviation Co. Ltd.) *Founder Member. Written contribution*: Opinions had been voiced from many quarters during the discussion on the controversial subject of whether or not the helicopter was difficult to fly.

It was generally agreed that in steady forward flight, apart from stability problems, there was not a great deal of difference between the rotary and fixed-wing aircraft, and it was on the question of hovering that the controversy arises. An examination in detail of the characteristics during this condition of flight might throw some light on the subject.

In the fixed-wing technique, discounting aerobatic manoeuvres, the condition of flight calling for the maximum concentration from the pilot and the most accurate co-ordination of aileron, elevator, rudder, and power controls, was the hold-off and touch-down to landing, occupying a period of perhaps a few seconds.

If the fixed-wing pilot considered the amount of concentration and co-ordination of control he needed to employ during this short hold-off period in order to ensure that the aircraft touched down to a perfect three-point landing, he would have some idea of what was required to hold a helicopter hovering, in just exactly that position, over an extended period of time.

Co-ordination of the controls in the helicopter was no more difficult than on the fixed-wing aircraft and became automatic with practice, but there would always remain the concentration, which was a source of mental fatigue. This theory had been borne out in practice and agreed with the experience acquired in helicopter crop spraying, which was a particularly tiring form of flying.

C. M. Britland (Royal Aircraft Establishment) *Written contribution* : Apart from the specialised and irregular uses of helicopters, such as crop-dusting, and looking at the possibilities for regular airline transport, they might learn much from studying Masefield's recent " treatise." Masefield was convinced that helicopters as they knew them now were of little value for this purpose when the block distance exceeded 200 miles, both from the economic and effective speed points of view. If they accepted his analysis they should either design helicopters specifically for such a short range or else overcome their fundamental handicap of low operating speed.

The first alternative suggested to him that they should energetically develop the jet-propelled rotor principle, since it was at short-range that such a device had superiority over the present system. Even with present knowledge the evidence suggested that they could build a jet helicopter which would hold its own economically with a reciprocating engine design over a stage length of about 150 miles, and they had not started to conduct serious research on jet-rotor problems yet, whereas the reciprocating engine was almost at the peak of its development. Many people were confident that the jet type would come out on top eventually and greater urge should be given to its successful development, and they should not wait for the Americans to prove its practicability. But perhaps it would be wise in the early stages to see how much noise would be acceptable over the peaceful English countryside !

The second alternative, of removing the handicap of low operating speed, could only be solved by the convertible aircraft in which, after take-off, the rotors were tilted through 90° to act as low-revving propellers while the aircraft was supported by small highly-loaded wings. He realised the complexity of such a concept, but this must be weighed against its many advantages. It could be the fastest form of inter-city transport for all distances up to 1,000 miles, except for the jet-propelled air liner at the longer ranges and it could combine the simple terminal requirements of the helicopter with the operational flexibility of a propeller-driven aircraft. For the critical take-off and landing operations at night or in bad weather, a convertible had the inherent safety of the helicopter and should practically eliminate the stacking problem. Such a machine, if proved practicable, would eventually outmode the present-day helicopter. Would it not be worth while, therefore, to examine the possibilities in detail at this early stage ?

Major J. L. B. H. Cordes *Founder Member. Written contribution* :

1. *Captain Liptrot's paper.*

Although he agreed with the major and technical part of this paper he would like to discuss further certain points on piloting—particularly from an aeroplane pilot's point of view. Aeroplane pilots did not find helicopters difficult to fly because they were afraid of losing speed as it was only a matter of doing so at a different time of flight. Every time an aeroplane landed it had to lose flying speed before it could touch down. He thought it was the gradual change of behaviour of the controls, when merging forward flight to hovering, that the pilot found rather puzzling at first. In forward flight the stick and pedals handled very much as they did in an aeroplane, but when hovering their functions altered considerable. The pilot's first sensations were rather like those of " Alice " when her knitting needles turned into oars, and he became confused. The actual loss of speed at this stage of instruction would not worry the pilot as he had already been taught to hover. The pilot was not afraid of losing speed while hovering as he had none to lose, and in any case the controls were so different under hovering conditions that the pilot found he was learning something entirely new and aeroplane habits did not worry him.

He had found that the comparison of the behaviour (not control) of an aeroplane to that of a helicopter was akin to a bicycle and that of a horse and there was no more difficulty in graduating from one to the other. The bicycle depended on its forward

speed for its equilibrium, and a change of heading for its change of direction ; whereas a horse (a nice one) could remain stable irrespective of speed, and would move forwards, sideways and backwards, and could even be persuaded to stay still, although attempts at hovering should be discouraged. The danger area too, to those on the ground, as with the helicopter, was in the vicinity of the tail.

The claim had been made that, in comparison with the aeroplane, the helicopter could not be stalled. Surely a wing, whether fixed or rotating, was stalled when the angle of attack was increased to such an extent as to induce a breakdown of the air flow over the top surface, resulting in a loss of lift ? The action taken to prevent this with either type of aircraft was the same in effect ; in the case of the aeroplane the angle of attack was reduced by putting the nose down, and in that of the helicopter by reducing the pitch of the blades. There was this difference, however ; if the increase in the angle of attack were persisted in, the aeroplane would stall, and if there were sufficient height, recovery would be made even from an incipient spin. On the other hand, with the helicopter under the same conditions, even before the blades reached their full stall the mean lift was great enough to overcome the centrifugal force that kept the blades horizontal, leading to " over-coning " and the collapse of the rotor—from which condition there was no recovery, from whatever height, and the question of when the blades fully stalled was not even of academic interest to the occupants !

2. *Safety.*

(*a*) *Parachutes.* It would be interesting to know what research had been, and was being, done to render the use of parachutes with a helicopter more feasible. There were certain conditions that could be visualised arising in flight, such as partial collision with another aircraft, a blade hitting a large bird, blade or hub failure, or, with Service aircraft, effects of hostile gunfire, where the use of parachutes would save life. Instructions to " jump clear in such a manner as to avoid the main rotor " were inadequate and, to his mind, a confession that a successful drill had not yet been evolved. The helicopter was flown more often than not, below " parachute height " but on those occasions when it was flown high enough to justify the carriage of a parachute it would be nice to know that use could be made of it easily if anything sufficiently serious occurred.

(*b*) *Reliability.* He would like to add every possible ounce of weight to the argument for at least two engines for commercial helicopters. He thought that one of the foremost and essential civil requirements of a helicopter was to be able to take short cuts with safety over built-up areas, rocky mountains, stormy seas or other unsuitable landing terrain. For this purpose it must be able to cruise at full load without losing height, on half its total engine power. It was also a requirement of the law pertaining to aircraft heavier-than-air. He would prefer the configuration of three engines with one rotor to three rotors with one engine. There was a practical comparison here with the aeroplane, where a tri-motored monoplane was obviously more reliable than a single-engined triplane.

G. H. Cumberbatch Willins *Member. Written contribution.* The transition from slow or hovering flight under power to autorotation with the minimum possible loss of height, following a power unit or transmission failure, should be regarded as absolutely fundamental to safety of operation. Had any tests been made to determine what proportion of the total height lost was needed for merely establishing " autogiro " flow pattern and a stable rate of rotation from the " helicopter " state of operation ? It would appear that this was a fraction of the height loss that must be accepted as inevitable, but it should be possible, by means of lower disc loadings and longer travel undercarriages, to save in emergencies the whole of that part lost in building up forward speed for a safe landing.

Mr. HAFNER had stressed the need for a definition of the permitted level of vibrations to keep within an agreed threshold of comfort. This was important since prolonged subjection to certain types of vibration could be very injurious ; and it would be advisable to take advantage of the latest medical research on the subject.

The remarkable safety record of the Autogiro had been referred to several times during the course of the discussion. It was interesting to recall that during their first ten years of development and establishment, Senor de la Cierva's Autogiros were flown in every part of the world by hundreds of pilots of all grades of experience, in schools, clubs, by private owners and on commercial operations without incurring a single fatal accident ; a record that must be unique in the history of Aviation, and one that would bear comparison with any other form of transport.

THE AUTHORS' REPLIES TO THE DISCUSSION.

Wing Commander Brie.

The criticisms which he had made arose from a close association with, and experience of, so-called modern equipment. If they looked back a little and delved into the nature of that equipment, no doubt they would get on to firmer ground. In the first place the Sikorsky S.51 was of American origin. Secondly it was a modified version of an aircraft conceived in 1942 for Service use, and soon after constructed in quantity under the stress of war conditions. Thus, although considered modern in the sense that it still had no more recent competitor, it was in fact much out-of-date compared with a completely re-designed version incorporating those obvious refinements resulting from " know-how " which could now be produced. It was remarkable that the S.51 was so good.

On the other hand and despite the rapid advances made elsewhere in the rotary-wing art during the past ten years, it was only comparatively recently that in Great Britain the potentialities of the helicopter had received anything like sufficient official attention and support. It was all very well blaming the war for this state of affairs, but in view of their pre-war achievements it ill behoved them to rely on such a flimsy excuse. Now somewhat tardily they had seen the light, and there were heartening indications that an effort was being made to make up as speedily as possible some of the leeway lost.

In this the B.E.A. Helicopter Unit was making a valuable contribution. The objective behind the acquisition of American equipment had been twofold. Firstly to ascertain the operational characteristics of the helicopter : whether, and in what manner, it could best be used : to study the economics of scheduled services : and to discover the problems, limitations, and difficulties. Secondly they wanted their efforts to act as an incentive to the British Industry to produce something which could be used with satisfaction. British European Airways now had over twelve months' experience in handling the Sikorsky S.51, and although current proposals for 10, 20, and even bigger passenger-carrying helicopters were attractive to contemplete, there were advantages to be gained by not trying to run before they could walk. The British Helicopter Industry had yet to acquire that valuable background of design and constructional experience based on past achievement. For the time being it would be something to shout about if only someone in Great Britain could demonstrate a prototype capable of performing no less efficiently than the S.51. On the other hand the operator could not acquire the desired standard of basic knowledge and experience unless he had the goods to handle. So that his criticisms arose from the deficiencies which he and his colleagues in B.E.A. had found in the equipment they were using. He saw many opportunities in a meeting such as this of pulling themselves to pieces : in fact he recalled a fairly recent article in the JOURNAL of the Institute of the Aeronautical Sciences showing how aeroplane interests got together and did exactly the same thing—but more so. They had competent technicians, engineers, and pilots, but it was up to the Industry to produce something worthwhile before expecting that additional encouragement in the shape of orders which normally followed solid achievement.

The point made by Group Captain Howard, who had asked why the British insurance companies should base their rates on what happened in America, was a good one. In B.E.A., in the course of twelve months' operation, they had not had to replace even a split pin as the result of an accident. That was a fact, and it was an achievement. Perhaps they had a better appreciation of the limitations of what they were handling.

He did not think it was easy to fly a helicopter. He knew of no other aircraft which was so easy to fly as the C30 Autogiro. When he took the first prototype to Martlesham Heath for its Certificate of Airworthiness tests he had sent off three pilots without giving them any dual instruction ; but that could not be done with the helicopter. During the evolution of the helicopter some very desirable Autogiro characteristics had been lost, and they had to retrace their steps a little.

With regard to the provision of landing sites in city centres, a point raised by Air Commodore Primrose, they must be careful not to put the cart before the horse. It was no use having the sites unless they had the aircraft. But he believed that Westland Aircraft and others were doing their best to fill the gap.

What they wanted was not only a helicopter with acceptable flying and performance characteristics ; they wanted also the advantages resulting from the healthy stimulus of competition. He felt quite sure that then the economics of the problem would look after themselves.

Captain Liptrot.

He agreed that what he and Wing Commander BRIE has said in their papers was rather coloured by what they had at present. They were using the equipment that was available, and from their experience of it they were trying to point the way and were trying to help others to appreciate what was being done in Great Britain in developing the helicopter. The British designers and constructors were showing that they were giving good engineering in the British helicopter. They were aiming at long life in the working parts, which meant low maintenance costs, and they were designing so that whole components could be taken out, repaired and replaced. Such factors showed that the British-designed helicopter was a sound engineering job; and the designers and constructors at the meeting had answered most of the questions put to them in the papers.

On the question of insurance rates in Great Britain, which appeared to be based on the accident rate in America, the accidents were not due to any intrinsic defects in the helicopter. So far as he was aware, in the whole development of the helicopter only seven people had been killed. That was a very low figure, and the helicopter was the only means of transport which in its early years of use had such a good record. Also on the credit side was the fact that the helicopter, in the two or three years of its operation, had been instrumental in saving well over 100 people.

They now had three helicopters of British design. Helicopters could not take their proper place in aviation until somebody built them in numbers. By giving the constructors the incentive to get a production line going, they could give enormous help to the development of the helicopter. The mere fact of getting a production line running would put the machine on the market; and once it got on the market, increasing numbers would be sold. When they reached that stage, down would come the price, and then it would become economical to the operator.

Dr. Bennett.

Mr. YATES had asked about the danger from engine failure at a height of less than 300 ft.; he happened to be visiting the Sikorsky Company in America on an occasion when there was an engine failure in a helicopter while hovering at a height of about 50 ft., and at a time when it was thought that 50 ft. was an unsafe height at which to hover. It was demonstrated on that occasion that that height was perfectly safe; the pilot had landed the machine and nothing much happened to it, except that the nose wheel was slightly damaged. There was no doubt that hovering at a greater height would be quite safe if the pilot took the proper action. It was advisable, however, not to rely entirely on the skill of the pilot and to incorporate the Gyrodyne features of low pitch, low rotor power and load disc loading. It was hoped eventually to ensure that a safe emergency landing could be made from any height by utilising the kinetic energy of the rotor before touch-down.

Mr. ROBERTS had referred to alleged inconsistency, in that the helicopter was required to have a high cruising speed for certain purposes, but not for others. There was no inconsistency about that. He thought that the Gyrodyne principle of independent propulsion would, in the future, enable considerably higher cruising speeds to be attained and that the development of blade tip jets would result in an improved slow-speed performance. It was manifest that those features, far from being incompatible, could be combined, and, as development work was now at an advanced stage, it would not be long before rotary wing aircraft showed a marked improvement at both ends of the speed range.

He agreed with Mr. WILLIAMS that the present helicopter had too many moving parts. Simplification was needed, not only from the safety point of view, but to reduce maintenance costs. This was possible with the torqueless rotor which, with the absence of mechanical transmission, would enable rotary wing aircraft to be operated reliably and economically on scheduled airline services both in built-up areas and over water.

In reply to Mr. EVANS, helicopters which were required to hover for long periods should either have an adequate reserve of power or be confined to operations where an engine failure would not be dangerous. Gas turbines, which might have to be incorporated in future helicopter designs simply for no other reason than that no suitable reciprocating engines would be available, offered certain advantages to the helicopter designer, one of which was that the helicopter could be designed to climb away vertically even if one engine failed.

Mr. Hafner.

The references to blind flying equipment brought him back to his question concerning the need for standardisation of controls. They could not get on with the design of helicopters if they did not know what was needed. His Company had built a number of mock-ups during the past few years which had been changed considerably from time to time, mainly because of the uncertainty as to what was needed. There was a definite need for an early agreement on standardisation.

He sympathised with Mr. TYE's feelings about present-day helicopter configurations, but they should remember they had only just started on this new venture. There was consolation in the fact that in this instance at least they did not depend for safety on the maintenance of speeds of the order of 100 m.p.h. The latter was something really worthy of rebellion. He thought that the tandem rotor configuration contained a fair measure of features with soothing effects on engineer's instincts. It was symmetrical, had a small frontal area and would look not unlike a streamlined railway coach that had decided to take the air.

He felt that the real solution to the stability of the helicopter was essentially a simple one ; he did not think the solution would be a gadget, but that there would be a sort of anti-climax. There was obviously a need for stability in forward flight but when hovering, the pilot was concerned with accurate control and had to maintain his position with regard to a point on the ground and, therefore, would not miss very much stability in that condition of flight. He felt that stability in forward flight would be obtained most easily by the conventional use of the tailplane. He had pointed out that within a certain speed range the Bristol 171 could be flown with hands off the controls. He hoped to be able to widen that speed range.

As helicopter engineering was developing rapidly and becoming progressively complex, it was important to prepare for the education of the young people now, and to ensure that this education was thorough.

The figures which Mr. ROBERTS had read in the graph on tip speed ratio as 1, 2 and 3 were actually 0.1, 0.2 and 0.3. The factor ζ did not refer to the deflection of the induced flow before the disc, but to the curvature (or the distribution) of induced velocity at the disc. ζ was defined in Ref. 1.

The technical developments of the helicopter and its ground equipment were interdependent. Thus, for example, the size of a helicopter and certain of its design details (*i.e.* undercarriage) were probably controlled by the rotor stations employed and *vice versa*.

He could not agree with Wing Commander BRIE that in the interest of safety in emergency landings it was particularly desirable to keep the rotor disc loading below 2 lb. per ft.^{2}.

It had been shown that the Bristol Type 171, notwithstanding the fact that its disc loading was over 2½ lb. per ft.^{2}, had excellent landing characteristics.

Dr. BENNETT had stated " helicopters which are rough in operation at high pitch in forward flight are usually quite smooth at the same forward speed in auto-rotation." He was surprised to hear this because he was of the opinion that collective pitch (or λ) was not a major factor in rotor vibrations. He could point out that the vibration level of the Bristol 171 was very low throughout the entire flight envelope. It was independent of λ, *i.e.* flying the aircraft in a flat glide and in low rotor pitch (which corresponded to the Gyrodyne condition of flight) was no better or worse than flying level or climbing.

He had come to the conclusion that the important speed limiting factors of a rotor were :—

Tip speed ratio
Basic lift coefficient
Mach number of the advancing blade tip
Coning angle

as could be seen from his paper.

He thought the range of danger heights had now been reduced practically to nil. He did not think the automatic reduction of pitch in a power failure was desirable, he thought it was dangerous, especially at high speed and near the ground. There was no need for a hurried reduction of blade pitch in a power failure, except during hovering at night, when every pilot instinctively would be alert and ready for an emergency.

The landing run of the Bristol 171 was practically nil; the forward speed was fully absorbed during the 10 seconds hovering prior to landing. Those auto-rotative landings were very comfortable; and he joined with others who urged that they might now safely dismiss outmoded ideas on auto-rotative landings.

In the design of the Bristol 171, great efforts were made to effect real simplification of components, not merely in order to make the aircraft cheaper to buy, but to reduce maintenance costs and to increase safety.

With regard to the auto-rotative landing shown in the graph, the glide, with the engine idling, began at about 5,000 ft. and at a height of 100 ft. the engine was switched off; so that throughout the whole descent the rotor was not driven by the engine.

He felt strongly that the helicopter might well supersede the fixed-wing aircraft for use on internal airlines. He did not agree with Mr. MASEFIELD's view that the helicopter would serve for journeys up to 200 miles only, beyond which the fixed-wing aircraft would take over, but thought that the helicopter would serve for journeys up to about 300 miles.

Mr. SHAPIRO had suggested that the tandem rotor arrangement was only marginally better than the side-by-side arrangement and, therefore, inferior to the three rotor configurations. He, on the other hand, had found that the weight and drag of an out-rigger structure for side-by-side rotors were extremely high and, therefore, the tandem rotor configuration was by far the best one for large shaft-driven helicopters.

Mr. SHAPIRO did not think the benefit of tip speeds beyond 550 ft./sec. was large. That was true for the hovering rotor. Many people, however, had pointed out the need for a high cruising speed and this could not be achieved without a high blade tip speed. The best performance of the Bristol 171 was obtained at a tip speed of over 700 ft./sec. and he thought this figure would increase as the art advanced.

Mr. Shapiro.

Mr. TYE was dissatisfied with the present state of knowledge on the subject of fatigue conditions in rotor blades. Long ago, Autogiro blades were designed on the scantiest information but the genius of the early workers Glauert, Loch and Cierva provided a basis for practical design. Studying subsequent investigations conducted by the R.A.E., he had been struck by the experimental confirmation of a brilliant approach. Autogiros had been flying for thousands of hours without a single failure attributable to blade fatigue. To-day analytical methods had been refined and measurements confirmed existing analysis even more closely.

There was no cause for lamentations in this field and he thought they knew as much of blade fatigue loads as they needed considering how little they knew of the behaviour of structures under prescribed fatigue loads. This shifted the emphasis to laboratory fatigue testing. But even there they could learn more if they heeded Sir HENRY TIZARD's and Mr. ROWE's advice on using existing knowledge. Some designs were amateurish and it was not surprising that failures had created the impression of lack of knowledge. Was this ignorance really necessary?

Mr. FITZWILLIAMS wanted talented volunteers from the ranks of aircraft engineers and many speakers seemed to want to go even further and breed a special race of helicopter designers. He disagreed: let them have *engineers*, craftsmen of the bench, the board, the laboratory and the desk, thoroughly familiar with fundamentals. Helicopter design was far too specialised an art to be taught at colleges, which should avoid specialisation *so far as possible*. Engineering applications should mainly serve as examples which, to be truly instructive, must be good, time-tested examples. He could not think of a worse example than the present-day helicopter.

Specialisation in helicopter design required a co-ordination and maturity of knowledge which could only be achieved in practice and through practice, unless they wanted young men capable of indulging in large scale scheming but incapable of attending to detail.

If specialisation were necessary let it be directed to types of activity rather than particular application. There was a case for vibration engineers, gear engineers and the like. He would like to create the profession of " stress physicist " and perhaps " fatigue engineer."

Helicopter design was a field wherein it was essential to discourage idle speculation by constantly keeping in mind the supreme question: how much? Opinions not expressible in quantitative terms were often worthless. Not only did the helicopter share with all aircraft the three-dimensional limitation due to its weight sensitivity, but it filled an intermediate gap in communications threatened on both sides by